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A Guide to Clean and Efficient Operation of Coal-Stoker-Fired Boilers

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Guidelines intended for use:

- by personnel responsible for boiler operation to perform an efficiency and emissions tune-up
- by plant engineers to initiate maintenance and efficiency monitoring practices
- as a supplement to manufacturer's service instructions

ABMA

EPA

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FOREWORD

This guide has been prepared by the American Boiler Manufacturers Association (ABMA) under contract to the United States Environmental Protection Agency and the United States Department of Energy to provide operators and owners of coal stoker fired boilers with information as to techniques and procedures which may be used to improve operating efficiency while reducing boiler emissions.

The guide was prepared under the supervision of the ABMA Stoker Technical Committee and is based on a program of field tests conducted as a part of research into factors affecting performance of stoker fired boilers. The principal author is Peter L. Langsjoen of KVB, Incorporated. Contributions of ABMA members have also been incorporated.

The contents of this guide are offered as guidance only. The American Boiler Manufacturers Association, KVB, Inc., and the United States Government and their employees do not assume responsibility or liability for consequences arising from the implementation or failure to implement the guidance contained herein. The contents of this guide should not be construed as an endorsement by the EPA, DOE or ABMA of any product or manufacturer.

This guide is intended as a supplement to the manuals furnished by the equipment manufacturers who should be consulted regarding operational or equipment problems.

William H. Axtman
Executive Director
American Boiler Manufacturers Association

ABSTRACT

This report was prepared as a set of guidelines for those in charge of operating coal stoker fired boilers. It explains and illustrates the different types of coal stokers in operation today. It explains the combustion process in simple terms, specifically as it relates to stoker coal combustion. It explains the various heat losses in stoker boilers and how they may be minimized. Most importantly, it discusses ways in which coal stoker fired boilers may be operated at peak efficiency and with minimum pollutant emissions. Included are step-by-step procedures for optimizing excess air levels.

The guidelines are based on the findings of an extensive coal stoker test program conducted for the American Boiler Manufacturers Association (ABMA) by KVB, Inc., between August, 1977, and November, 1979. This report was submitted in partial fulfillment of Contract No. IAG-D7-E681 (EPA) and EF-77-C-01-2609 (DOE).

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This document has been reviewed and approved for publication by the Stoker Technical Committee of the American Boiler Manufacturers Association (ABMA), by the U. S. Environmental Protection Agency (EPA), and by the U. S. Department of Energy (DOE). This document was written by KVB, Inc. The principal author was P. L. Langsjoen, P.E..

SECTION 1

INTRODUCTION

This manual has been written for boiler operators and is intended to be a concise, easily understood and interesting guide to the clean and efficient operation of bituminous and sub-bituminous stoker coal-fired boilers. It should be made very clear, however, that this manual neither replaces nor supercedes the manufacturer's operating manual for your boiler. The manual will explain general principles of boiler operation and will suggest ways of reducing boiler emissions and increasing boiler efficiency. But the manual will not show you how, exactly, to implement these suggestions. For that you must consult your boiler manufacturer's operating instructions. You, then, must decide how to implement a sensible emission control and/or boiler efficiency program.

The first section of the manual describes the types of stoker boilers in use today. Since stokers of different design have different operating characteristics, this part of the manual will explain the peculiarities of each type of design so you can better understand how to deal with problems specific to the type(s) of stoker you are operating. The next section of the manual explains, in a concise and simple way, the combustion process. Understanding this process will allow you to control it better. Since both increased boiler efficiency and reduced boiler emissions can be achieved most inexpensively through combustion control, a basic understanding of the combustion process is essential to achieving improved boiler operation. The last two sections of the manual explain how you can control the combustion process in your coal stoker-fired boiler in such a way as to achieve increased boiler efficiency and reduced emissions. While it is frequently possible to achieve increased efficiency and reduced emissions simultaneously, there is sometimes a tradeoff between the two. The nature of this tradeoff is explained in the last two sections of the manual.

This document draws upon the extensive experience gained during the industrial coal stoker-fired boiler test program conducted by KVB, Inc., for the American Boiler Manufacturers Association (ABMA). (Ref #1-12)

SECTION 2

STOKERS IN USE TODAY

In the early days, a "stoker" was someone employed to tend a furnace. To stoke a fire meant to do whatever was necessary to keep it burning properly, including poking, stirring, and supplying it with fuel. Eventually these "stokers" were replaced with mechanical devices which automatically fed fuel to the furnaces, and in some cases automatically disposed of the ash. These were called mechanical stokers, and first appeared in the 1800's.

Today, there are a variety of mechanical stokers in use. They differ in the way in which solid fuel is fed onto the grate, and they differ in the way in which ash is removed from the grate. Each method of firing has its own unique operating characteristics, and each has its own best applications. This section will discuss the types of mechanical stokers which are commonly used today for firing coal.

Today's stokers can be sorted into three categories based on the way in which fuel is fed onto the grate. These categories are: (1) underfeed stokers, (2) overfeed stokers, and (3) spreader stokers. Within each category, the stokers differ according to the way in which the grate handles the ash. Each stoker category will be discussed, and the most common stoker types will be illustrated.

UNDERFEED STOKERS

In an underfeed stoker, the fuel is introduced through long troughs, called "retorts", at a level below the location of air admission to the fuel bed. Thus, the green coal (or raw coal) is at the bottom, the ash moves away from the retort, and combustion takes place in between, constantly receiving a fresh supply of green coal from below and displacing the ash.

Underfeed stokers were developed in the 1800's, and were very popular before World War II. After World War II, they were gradually replaced by larger spreader stokers and overfeed stokers. However, they have many useful applications and are still being sold today.

The smallest of the underfeed stokers have a single or double retort into which the coal is fed. The coal feed is by either a screw or a mechanical ram which forces the coal the length of the retort and upward. The ash on this type of stoker is normally discharged with side dumping grates. These stokers will fire boilers in the size range of 3,000 to 30,000 pounds of steam per hour.

Figure 1 shows what a typical single retort stoker looks like, and Figure 2 shows a cross section of this stoker in a furnace and how it would look in operation. Note how the ash moves to the sides where it can be periodically dumped into ash pits and removed. Note also that the "tuyeres", through which air is admitted, are above the retort.

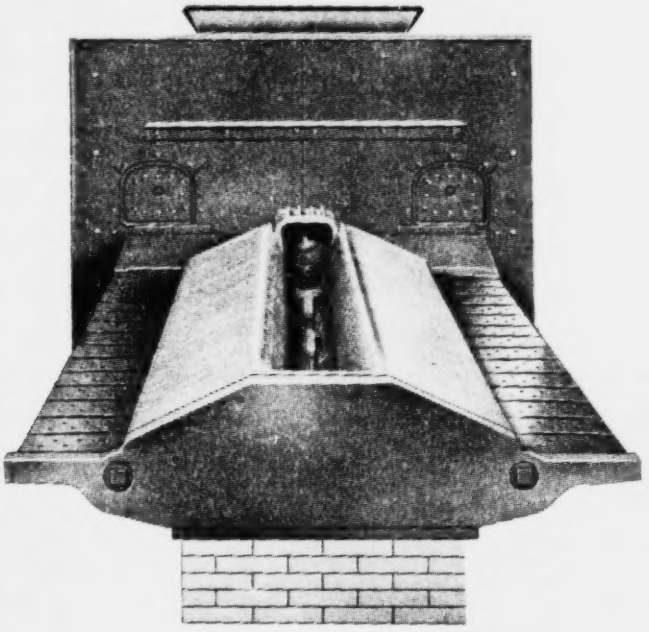

Figure 1. Single Retort Underfeed Stoker with Side Dumping Grates. (Reprinted with Permission of Detroit Stoker Company)

Some underfeed stokers have grate sections which have an undulating (wave-like) action to break up clinkers from high-coking coals so that manual poking is reduced. Most modern underfeed stokers are also equipped with overfire air jets to provide turbulence to mix the volatiles with the air for more complete combustion.

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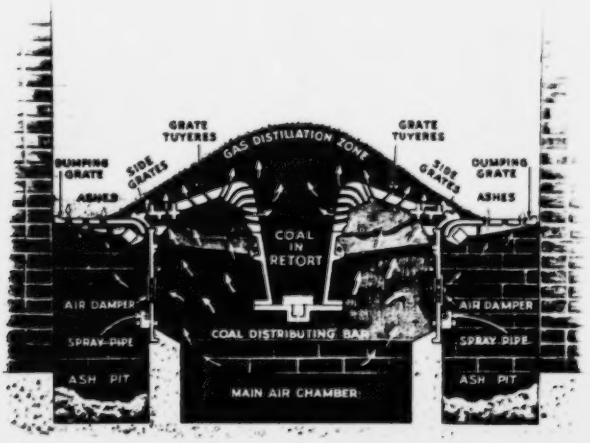

Figure 2. Cross-Sectional View of Single Retort Underfeed Stoker in Operation. (Reprinted with Permission of Detroit Stoker Company)

The larger underfeed stokers are of the multiple retort type having as many as twelve retorts inclined at an angle of 25° to 30° to aid the movement of coal and ash. Illustrations of this type of stoker are given in Figures 3 and 4. In this type of stoker, the ash is discharged at the rear either intermittently with a dumping grate or continuously as it is displaced by the burning coal.

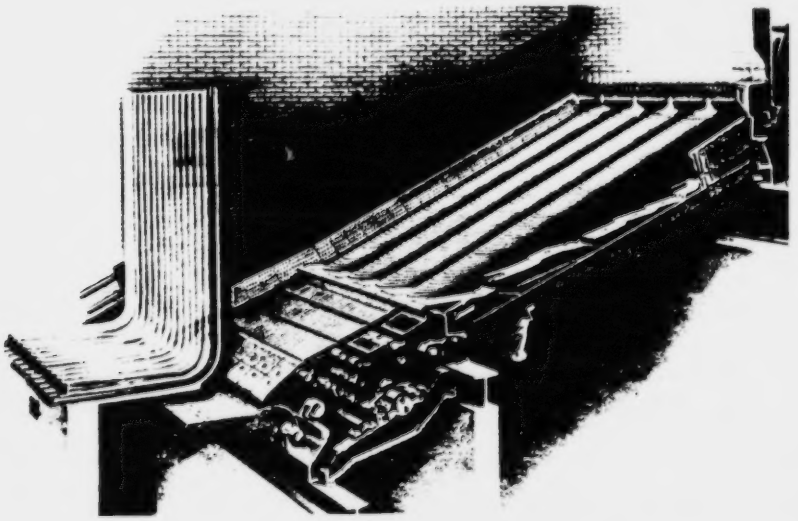

Figure 3. Multiple Retort Underfeed Stoker Showing Details of Components. (Ref #13) (Reprinted with Permission of Detroit Stoker Company)

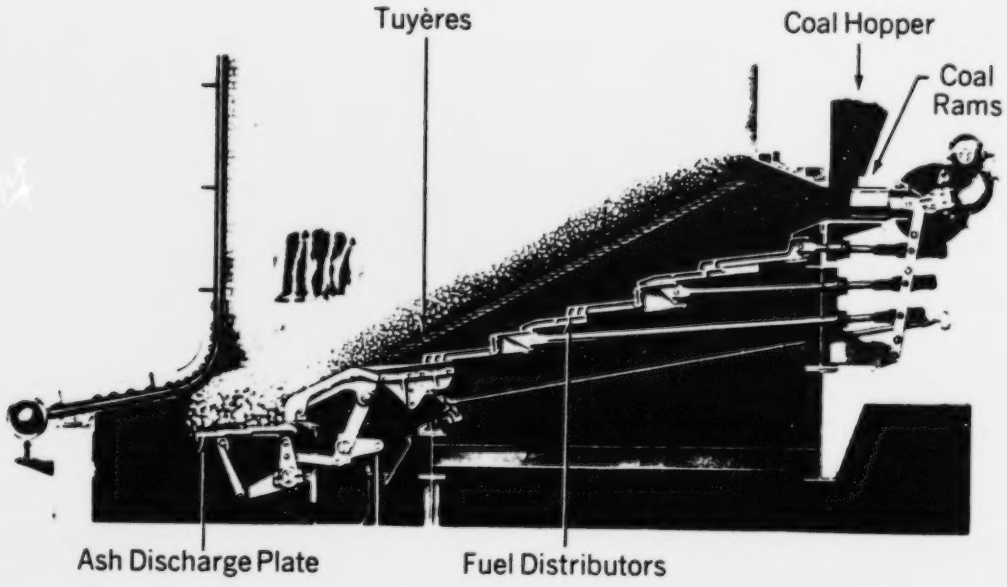

Figure 4. Side View of Multiple Retort Underfeed Stoker. (Ref #14)
(Reprinted with Permission of Detroit Stoker Company)

The multiple retort stoker employs large mechanical rams and pusher blocks to feed and distribute the coal. It also employs overfire air when necessary. These units are used in boilers which range in size from 20,000 to 500,000 pounds of steam per hour.

It can be seen from Figures 2 and 4 that underfeed stokers operate with very thick fuel beds. This results in a high thermal inertia, or a slow response time to changes in steam loading. They also have trouble burning certain grades of coal, such as high-coking coals, which form a coke that expands and arches off the grate, and free burning sub-bituminous coals whose loose ash leave sections of the grate bare causing overheating and grate damage. Low ash bituminous coals when burned may not generate sufficient ash to protect the grate surface.

On the positive side, underfeed stokers have a clean smokeless combustion when fired with the proper coals, and they have low flyash carryover. The smokeless combustion results from feeding the coal from underneath the combustion zone. As the coal is heated, the volatiles are driven off and pass upward through the incandescent, burning coals where most are consumed before they pass completely through the fuel bed.

OVERFEED STOKERS

In an overfeed stoker, the coal is fed onto the grate above the point of air admission. The two basic types of overfeed stokers are the chain, or traveling grate stoker, and the water-cooled vibrating grate stoker. Technically, a spreader stoker is also a type of overfeed stoker. However, because it is commonly considered in a class by itself due to its unique features, it will be classified separately in this text.

A typical chain grate overfeed stoker is illustrated in Figure 5. It consists of a continuously moving grate. Coal is deposited on one end of the grate by gravity feed from a coal hopper. The coal depth is adjusted by a guillotine-like movable coal gate to a thickness of about 4 to 12 inches. The coal is burned as it passes slowly through the furnace at grate speeds of less than 30 feet per hour. The ash is continuously discharged off the rear of the grate into an ash pit.

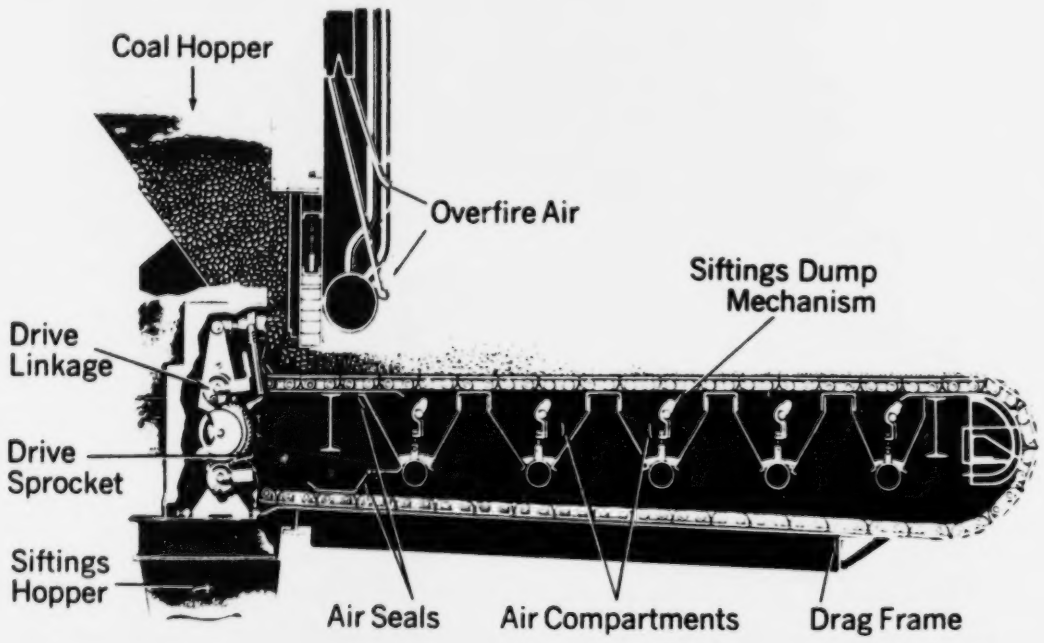

Figure 5. Side View of Chain Grate Overfeed Stoker. (Ref #14)
(Reprinted with Permission of LacLede Stoker Company

There are different types of grate construction in use. These are classified either as chain or traveling grates, although the chain grate also travels. In the chain grate, the grate itself is a wide chain composed of close-fitting links. The air passes upward through the spaces between the links. In the traveling grate, grate sections called "bars" or "links" are attached to a separate chain. A typical traveling grate stoker is illustrated in Figure 6.

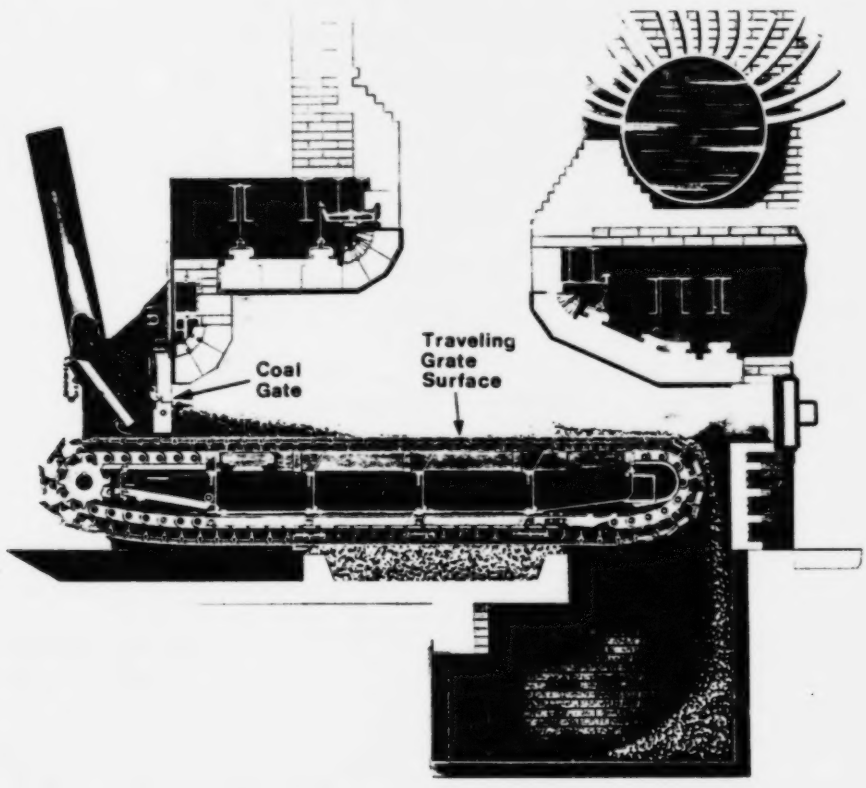

Figure 6. Side View of a Traveling Grate Overfeed Stoker. (Reprinted with Permission of Riley Stoker Corporation)

Undergrate air is controlled through individual air zones or compartments underneath the grate. The amount of air entering each zone is manually controlled by the operator. Many of the overfeed stoker-fired boilers have a rear arch which directs any remaining volatile gases and cinders from the burnout zone back towards the flame zone where they may be burned. One or two rows of high-pressure overfire air jets are used on the front waterwall to mix the volatiles with the air for more complete combustion. Chain and traveling grate stokers have been built for boilers as large as 200,000 pounds of steam per hour.

The water-cooled vibrating grate stoker uses vibration and gravity to move the coal. This type of stoker originated in Europe and was introduced to the United States in the mid 50's. It is illustrated in Figure 7.

It consists of a water-cooled grate supported by flexing plates and inclined at an angle of about 14°. Coal is gravity fed at the top of the grate and passes under a guillotine-type gate which controls the bed thickness. The grate is vibrated for about 5 seconds every two minutes. The interval and duration of the vibrations is tied to the automatic controls, and determines the rate at which the coal is moved through the active burning zone. Ash is discharged at the rear of the stoker.

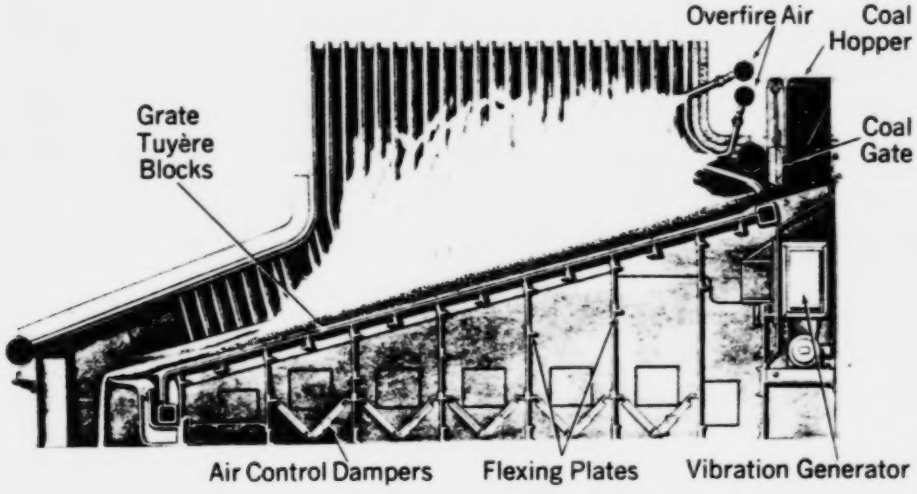

Figure 7. Side View of a Water-Cooled Vibrating Grate Stoker. (Ref #14)(Reprinted with Permission of Detroit Stoker Company)

As with the chain and traveling grate stokers, the vibrating grate stoker has individually controlled air zones. The boiler often has a rear arch to direct any remaining volatile gases from the burnout zone back into the active combustion zone. It also uses high-pressure overfire air jets on the front wall to promote mixing of the volatile gases and the air for more complete combustion.

In general, overfeed stokers are characterized by low flyash carryover. They burn most coals, although high-coking coals may be a problem. The overfeed stoker's response time to rapid changes in load is slower than that of the spreader stoker, and such stokers require a larger grate size for a given heat input than a spreader stoker.

SPREADER STOKERS

In a spreader stoker, coal is spread evenly over the entire grate surface by mechanical feeders located at the stoker front above the grate. Because the coal is thrown onto the grate, there is some suspension burning of the coal fines. This suspension burning coupled with a very thin fuel bed allows the spreader stoker to respond to rapid load changes.

There are many types of mechanical feeders in operation. They all utilize rotor speed and coal trajectory to adjust coal distribution on the grate. One type of mechanical feeder is illustrated in Figure 8. In this typical arrangement, coal is pushed over the edge of a "spill plate" onto a rotating "overthrow rotor". The rotor has paddles on it and is spinning at several hundred revolutions per minute. As the coal moves over the "spill plate", it is struck by the paddles and is thrown into the furnace. The paddles are designed to distribute the coal over a wide area. The rotor speed, spill plate position, and sometimes the paddle orientation can be adjusted to provide an even distribution of coal on the grate. The number of feeders used depends on the width of the stoker grate.

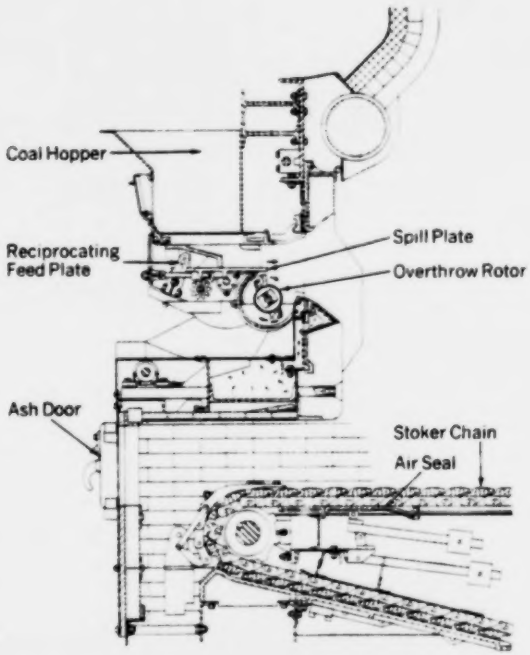

Figure 8. Side View of a Mechanical Coal Feeder Showing Components. (Ref #14)(Reprinted with Permission of Detroit Stoker Company)

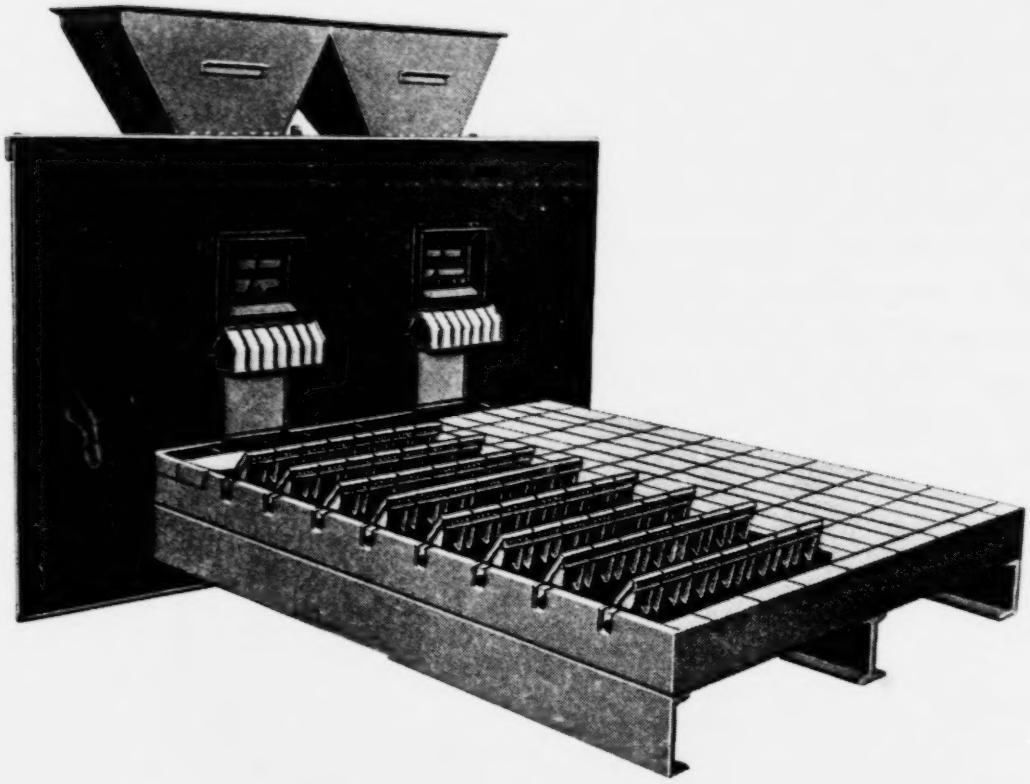

Figure 9. Dumping Grate Spreader Stoker. (Reprinted with Permission of Zurn Industries, Inc.)

Spreader stokers include a wide variety of grate types. One type is the dumping grate spreader stoker. The grate bars on a dumping grate stoker rotate open like Venetian blinds so that the ash will fall into an ash pit underneath the grate. As illustrated in Figure 9, this type of stoker is built with two or more independent dumping sections. When the ash builds up on one section, the coal feed is stopped to that section and the fire allowed to burn down. At the same time, the coal feed is increased to the other sections to prevent a drop in steam pressure. When the fire has burned down on the one section, the undergrate air is shut off to that section only, the ashes dumped, and the air and coal feed resumed. When the fire has been reestablished on the dumped section, the process is repeated on the other sections. Dumping grate stokers have been built for boilers in the size range of 15,000 to 75,000 pounds of steam per hour.

The larger coal-fired spreader stokers use continuous ash discharge grates. The most popular version of this type of grate is the traveling grate. Reciprocating grates and vibrating grates are also sold but are less popular.

A typical arrangement of a spreader stoker with traveling grate is illustrated in Figure 10. Note that the ash is discharged at the front of the stoker rather than at the rear. The spreader stoker is usually equipped with overfire air jets front and rear to provide turbulence for mixing the volatile gases with the air, and to hold the flames off the water walls and out of the feeder throat. Spreader stokers are usually not equipped with separately controlled undergrate air zones because these have been found to be generally unnecessary. Traveling grate spreader stokers have been built for boilers as large as 400,000 pounds of steam per hour.

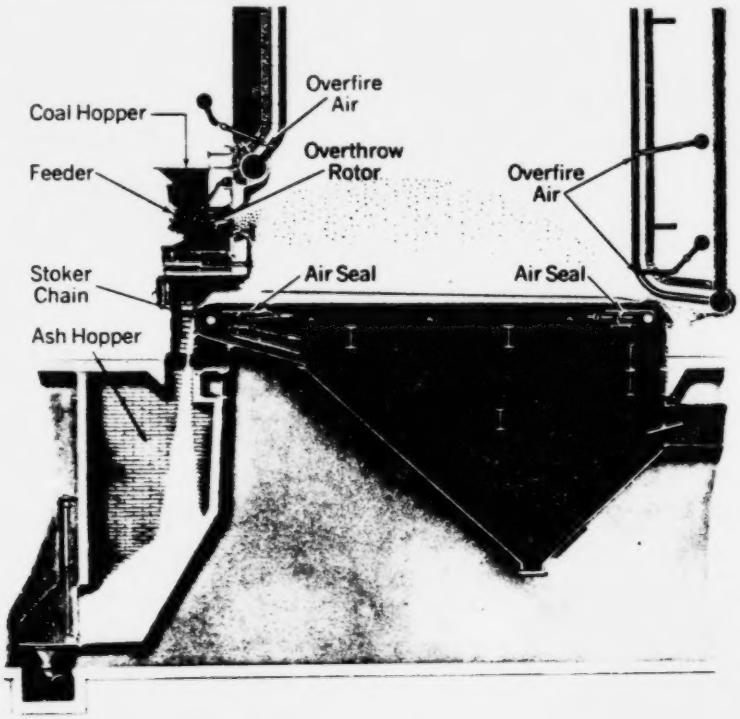

Figure 10. Side View of a Spreader Stoker with Traveling Grate. (Ref #14) (Reprinted with Permission of Detroit Stoker Company)

The spreader stoker is characterized by a thin bed and partial suspension burning. As a result, it responds rapidly to changes in load. It is capable of firing a wide range of coal grades and types. The spreader stoker has high availability, simplicity of operation, and high operating efficiency, but it has high flyash carryover and a high flyash combustible heat loss. Cinder reinjection is used on spreader stokers to recover some of the carbon in the collected flyash.

SECTION 3

THE COMBUSTION PROCESS

Combustion is a chemical reaction in which oxygen combines rapidly with elements in the fuel to form new compounds and heat. This heat is used to produce steam or hot water in boilers. The new compounds, or products of combustion, are primarily carbon dioxide and water vapor which exit the boiler through the stack.

It is the boiler operator's job to maintain the safety and efficiency of the combustion process, and to minimize the undesirable products of combustion such as carbon monoxide, nitric oxides and particulates to name just a few. To do this, the operator must understand the combustion process. He need not have the technical background of a combustion engineer, but he does need to understand how his actions affect the combustion process. That is what this section is all about.

THE CHEMICAL REACTION

First, let's look at combustion on a molecular level to see what is happening.

Consider the combustion of carbon. Carbon (C) combines with oxygen (O_2) to form carbon dioxide (CO_2). This reaction releases energy in the form of heat. A chemist writes the reaction equation like this:

$$C + O_2 \rightarrow CO_2 + \text{heat}$$

That's fine, you might say, but there is oxygen in the air and carbon in this lump of coal so why don't they react and ignite in my hand? The reason they don't react at room temperature is that there is a barrier between the carbon atoms and the oxygen molecules which keeps them apart. The carbon and oxygen must collide with enough energy to overcome this barrier before they will react. The energy required to overcome the barrier is heat energy.

Exactly what is heat? Heat can be thought of as motion on a molecular level. When something is heated up, its molecules move around or vibrate more vigorously. For example, when a hot object touches something cooler, it transfers some of its energy of motion to the cooler object. The combined energy of the

two objects remains unchanged. Therefore, the hot object cools and the cool object heats up until their molecular motion are the same. Then they are at the same temperature.

In the chemical reaction of carbon and oxygen, it takes a certain amount of heat energy to overcome the barrier, but once the barrier is overcome, a larger amount of energy is released. The result is a net gain in energy. A good analogy is pushing a cart over the crest of a hill. The cart won't roll down the other side until it is pushed over the crest. So you put a little energy into the cart to get it over the crest but gain much more energy as the cart rolls down the other side of the hill. This analogy is illustrated in Figure 11.

Figure 11. Analogy of a Chemical Reaction

THE COMPOSITION OF COAL AND AIR

Coal has more than just carbon in it, and air has more than just oxygen. Therefore, the combustion of coal involves a number of chemical reactions. First, let's look at what coal and air are composed of. This is shown in Figure 12.

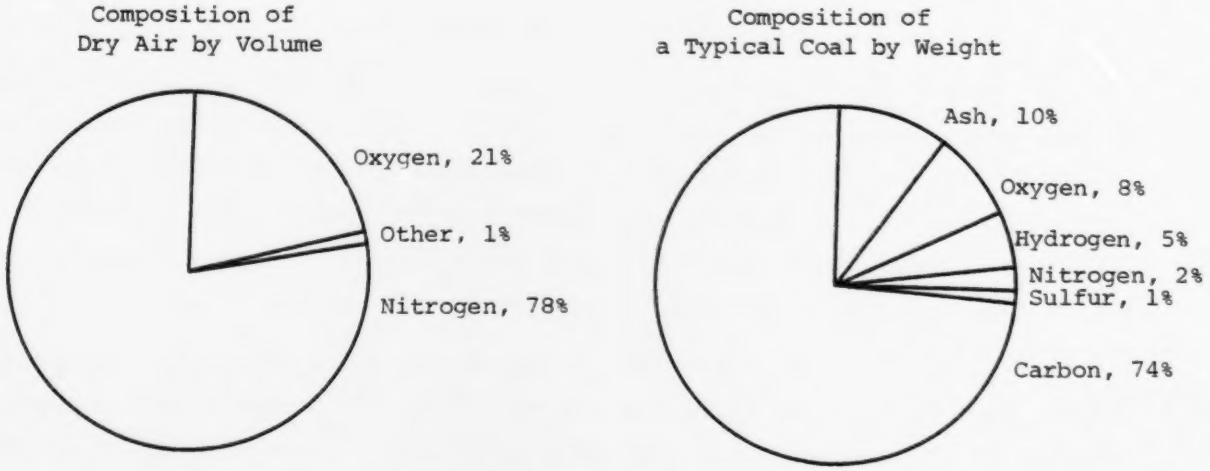

Figure 12. Composition of Dry Air and a Typical Coal

The important reactions for producing heat from coal involve carbon (C), hydrogen (H_2), and oxygen (O). There are other reactions which occur, but these don't add much to the heating value of the coal. These minor reactions are responsible for some of the air pollutants and are explained later. The primary heat producing reactions are:

$$O_2 + C \rightarrow CO_2 \quad + \text{ 14,100 Btu per pound of carbon}$$
$$O_2 + 2H_2 \rightarrow 2H_2O \quad + \text{ 61,100 Btu per pound of hydrogen}$$

This means that the flue gas is mostly carbon dioxide (CO_2), water vapor (H_2O), and nitrogen (N_2). Where did the nitrogen come from? Most of the nitrogen in the air did not react with anything, it just passed through the boiler. A typical flue gas from a coal-fired stoker might contain:

Typical Flue Gas Analysis

12% carbon dioxide	(CO_2)
6% water vapor	(H_2O)
74% nitrogen	(N_2)
8% oxygen	(O_2)

STEPS IN THE COMBUSTION OF COAL IN STOKER-BOILERS

In actual practice, the combustion of coal is more complex than meets the eye. The following events take place when coal is burned in a stoker.

Moisture is Driven Off

Moisture is driven off from the coal when it first enters the hot furnace. The more moisture there is, the longer it takes for the coal to heat to its ignition temperature and, thus, the harder it is to ignite the coal.

The process of removing the moisture from the coal is similar to boiling water on the stove. The water and its container remain at 212°F until all the water has been boiled off because the vaporization of the water absorbs heat as fast as it is added. Only when all the water has boiled off will the pot heat up further. Likewise, the heating of the coal is slowed down by the vaporization of its moisture.

While on the subject of moisture, it is worthwhile noting that there are two forms of coal moisture. There is surface moisture produced by conditions at the mine or by rain, and there is inherent moisture which is a part of the coal and which does not produce wetness. Inherent moisture is usually found in the following concentrations: (Ref #15)

Bituminous Coals	2 - 17% moisture
Sub-bituminous Coals	15 - 30% moisture

Volatiles are Driven Off

As the coal continues to heat up, it partially decomposes giving off gases. These gases are called its volatile matter. Typically, 20 - 40% of the coal's weight becomes volatile matter. Some of this volatile material is noncombustible, but most of it will burn. The combustible gases include hydrogen, carbon monoxide and hydrocarbons such as methane.

The volatiles help to ignite the coal in the same way that kindling helps to ignite a log fire. The volatiles have a lower ignition temperature than the coal, so when the coal enters the furnace, the volatiles are driven off and ignite first. The heat from the burning volatiles heats up the rest of the coal to its ignition temperature.

Combustion of the Volatiles

The volatiles will produce a different kind of flame depending on how rapidly they are heated and how they are mixed with oxygen.

For example, if the volatiles are heated very rapidly and are slow to mix with the oxygen, they produce a yellow flame. This is because the high temperatures split the hydrocarbon molecules apart (called cracking by chemists) into separate carbon and hydrogen molecules. The hydrogen burns almost instantly to form water vapor, but the carbon is slower to combine with the oxygen. The tiny carbon particles glow or incandesce until burned, giving the flame its yellow appearance. If these carbon particles leave the flame without being burned, they are called soot.

Another kind of flame is produced when the volatiles are well-mixed with oxygen and are heated more slowly. Under these conditions, the hydrocarbon molecules combine with oxygen first and then split apart into water vapor and carbon dioxide. Because there is no free carbon floating around, there is no soot and no yellow flame. The flame produced is blue.

The blue flame is best, because it is the cleanest burning. However, in coal combustion, both combustion sequences are always present and the coal flame is usually yellow-orange in appearance.

Anyone who has played with a bunsen burner knows how to produce both kinds of flames. If the air ports are closed at the base of the burner, a yellow sooty flame is produced because the hydrocarbons split apart before they burn. But when the air ports are opened so that the gas and air are premixed before they reach the flame, the flame is blue and produces no soot.

Combustion of the Coke

What remains after the volatiles have been driven off is primarily carbon and ash. This is called coke. The carbon is called "fixed carbon" because it wasn't driven off with the volatiles. Fixed carbon does not vaporize before it burns; it would require 6300°F to vaporize the carbon in the coke, whereas furnace temperatures are less than 3200°F. Instead, oxygen attaches to the surface of the coke and breaks away as carbon-oxygen compounds.

If there is plenty of oxygen available, carbon dioxide (CO_2) is formed at or near the surface of the coal and there is no flame. Like a good charcoal fire or a smoldering log, combustion takes place very near the surface.

If there is not enough oxygen to go around, some of the carbon is only partially oxidized. That is, it only reacts with one oxygen atom instead of two, forming carbon monoxide (CO). This is bad for two reasons. It is a waste of fuel because carbon releases less than 1/3 of its energy when it reacts with only one oxygen atom; and secondly, the carbon monoxide formed is a safety and health hazard.

Fortunately, most of this carbon monoxide will be burned to carbon dioxide as it passes up through the flame zone created by the other burning volatiles.

REQUIREMENTS FOR COMPLETE COMBUSTION

Four requirements must be met before complete combustion will take place. These are proper fuel-air ratio, turbulence, temperature, and time. The last three are commonly called the 3 T's of combustion.

Fuel-Air Ratio

A combustion engineer can calculate the exact amount of air required to burn any coal if he knows the chemical analysis of that coal. This "Theoretical Air" (sometimes called stoichiometric air) would contain the exact amount of oxygen required to burn all the combustibles in the coal.

In actual practice, the fuel always needs more than the theoretical amount because mixing of the fuel and air is not perfect. Stokers generally require 30% to 50% more air than the theoretical minimum in order to prevent incomplete combustion at high loads. At low loads, an even higher percentage of "excess air" is required.

A proper fuel-air ratio is necessary to support complete combustion. If there is too little air, the result is smoke, carbon monoxide and clinkering on the grate. If there is too much air, the result is low boiler efficiency and cooling of the flame. The ideal is to operate with as little air as possible without creating excessive smoke, carbon monoxide, or clinkering.

Turbulence

It does no good to have a proper fuel-air ratio if the air is not properly mixed with the fuel. It often happens that streams of fuel-rich gases will rise in one area of the fuel bed while streams of air-rich gases will rise in another. Without turbulence to even mix the combustible gases with the air, combustion will be incomplete. The result will be excessive smoke, high carbon monoxide emissions, and low boiler efficiency.

Overfire air jets are installed on most modern stoker equipment to provide this turbulence. Arches are used in some boiler designs to direct the hot volatile gases to the flame zone. This is another means of providing mixing, or turbulence.

The fixed carbon on the grate also requires the movement of air. Without this movement, a layer of carbon dioxide and carbon monoxide forms around the coal making it difficult for oxygen to penetrate. Air movement strips away this gas layer and provides a fresh supply of oxygen. Have you ever noticed how blowing on a charcoal fire increases the combustion dramatically? This illustrates the same principle.

To insure an even and constant distribution of air to the coals, grate air holes must be kept unplugged, warped or broken grate sections must be replaced, and clinkers must be broken up. Also, coal must be evenly distributed on the bed because the air will flow through the areas of least resistance and starve the areas of most resistance. This is very important.

Ignition Temperature

Before combustion begins, the fuel must be heated to its ignition temperature. This is the temperature at which more heat is generated by the chemical reaction of combustion than is required to sustain ignition.

As an example, consider a lump of coal held in your hand. This coal is in contact with the air and is reacting with oxygen in the air. This reaction is giving off heat. But, the reaction is extremely slow at room temperature and the heat is carried away as soon as it is formed. So, the lump of coal never heats up and the chemical reaction remains imperceptably slow.

Now, consider this same lump of coal inside a coal pile. Again, it reacts with the oxygen which surrounds it inside the pile. But now the lump of coal is insulated by the surrounding coal in the pile. Under these conditions, heat from the slow oxidation of the coal may be generated faster than it can be carried away because of the insulating effects of the surrounding coal. When this happens, the lump of coal becomes slightly warmer and the rate of oxidation increases slightly. You can see what happens next, the coal gets hotter and the reactions get faster until the ignition temperature is reached and a fire begins in the coal pile. This same reaction can occur with oily rags placed in a confined container. It's called spontaneous combustion.

In a coal-fired stoker, the operator is concerned with maintaining complete combustion. If a flame is cooled too fast, combustion will be incomplete. The flame will be quenched before all the chemical reactions have taken place. The result is smoke from unburned carbon particles, and high concentrations of carbon monoxide.

One way a flame is cooled too fast is when it touches (or impinges on) a cold water wall. Flame impingement is prevented by adjusting overfire air jets to push the flame away from the water wall, or by adjusting the undergrate air zones, or by changing the coal distribution pattern in the case of spreaders. Very high excess air can also lower the temperature enough to cause incomplete combustion.

Time

Combustion is not instantaneous. It takes time for the oxygen molecules to collide with (and react with) the carbon and hydrogen molecules. The time required is less if turbulence is present, if temperatures are higher, and if the fuel-air ratio is proper. Time and temperature go hand-in-hand. The volatile gases must be above their ignition temperature for sufficient time to complete combustion. If the flames impinge on the water walls before they have had time to complete combustion, the result is smoke and high carbon monoxide emissions.

It also takes time for the fixed carbon on the grate to burn. The time required is shortened when the excess air is increased. Grate speed (on traveling grate units) and undergrate air distribution are adjusted to allow the fixed carbon to burn to completion.

PRODUCTS OF COMBUSTION

There are eight common products of combustion which make up the flue gas of all coal-fired stoker boilers. Each one is discussed below. The first two, carbon dioxide and water vapor, are harmless gases and necessary products of combustion. The remaining six are always present to some degree, but they should be minimized because they either reduce boiler efficiency or they are considered pollutants.

Carbon Dioxide (CO_2)

This is a harmless gas which results from the complete combustion of carbon. The chemical reaction is: $C + O_2 \rightarrow CO_2$ + 14,100 Btu per pound of carbon burned. This reaction is responsible for 78% of the heat released from a typical coal.

Water Vapor (H_2O)

This harmless vapor results from the combustion of hydrogen. The chemical reaction is: $2H_2 + O_2 \rightarrow 2H_2O$ + 61,100 Btu per pound of hydrogen burned. This reaction is responsible for 22% of the heat released from a typical coal.

Nitrogen (N_2)

Most of the nitrogen in the air is carried through the boiler without reacting with oxygen. It makes up about 75% of the flue gas by volume. The added weight of the nitrogen increases the amount of heat carried out the stack and in this way reduces boiler efficiency. It also adds to the volume of flue gas and wastes fan power. For these reasons, nitrogen should be kept at a minimum by keeping excess air at a minimum.

Oxygen (O_2)

There is always some oxygen left over after combustion. In stoker-boilers, the operator is doing well to keep the oxygen in the 5-7% range. This unused oxygen reduces the efficiency of the boiler in the same way that nitrogen does. Every extra pound of oxygen brings with it 3.3 extra pounds of nitrogen, and this "excess air" absorbs heat which could otherwise have been converted to steam, and carries it out of the stack.

Carbon Monoxide (CO)

This gas results from incomplete combustion of carbon: it's wasted fuel going out the stack. When one carbon atom combines with only one oxygen atom, it releases only 28% of its heat. The other 72% is lost. Carbon monoxide is also a health hazard when inhaled in high enough concentrations, and a safety hazard because it can form explosive mixtures in high concentrations.

SOx: Sulfur Dioxide (SO_2) and Sulfur Trioxide (SO_3)

This gaseous emission is formed from combustion of sulfur in the coal. The chemical reactions release heat which add slightly to the heating value of

$$S + O_2 \rightarrow SO_2 + \text{Heat}$$
$$2\ S + 3O_2 \rightarrow 2SO_3 + \text{Heat}$$

a typical coal. Unfortunately, these sulfur oxides are harmful to plants and animals. The SO_3 combines readily with water vapor to form sulfuric acid which is very corrosive, and which contributes to the acid rain problem.

One way to reduce this emission is by purchasing a lower sulfur coal. Another way is to install a sulfur scrubber. Fuel additives have been used to retain some of the sulfur in the ash and thus reduce the SOx emissions. Washing the coal may also lower its sulfur content and thus reduce SOx emissions.

NOx: Nitric Oxide (NO) and Nitrogen Dioxide (NO_2)

This gaseous emission can be partially controlled in stokers by reducing the excess air. Nitrogen oxides are formed from both the nitrogen in the fuel and the nitrogen in the air. These chemical reactions add nothing to the heating value of the fuel.

$$2\ N + O_2 \rightarrow 2\ NO$$
$$N + O_2 \rightarrow NO_2$$

Unfortunately, it doesn't take much NOx to form photochemical smog, so this pollutant is highly undesirable. It also contributes to the acid rain problem.

Particulate Matter

Particulates are solid particles of flyash carried along with the flue gas. They may contain some carbon which when carried out the boiler reduces the boiler efficiency.

Particulate matter can be reduced by proper stoker-boiler operation. Mechanical dust collectors, baghouses, and electrostatic precipitators are also used to collect particulate matter before it goes out the stack.

SUMMARY

The operator's job will be easier and more enjoyable if he understands the combustion process. The more he knows about combustion, the better control he will have over it.

SECTION 4

BOILER EFFICIENCY

Most stoker fired boilers are between 65% and 85% efficient in converting the coal's energy into steam. This means that much of the coal's energy is wasted. Some of this waste is unavoidable, as we will see, but some of it can be avoided if the operator understands how it occurs.

"Heat loss" is the term used to describe the way energy is wasted. Figure 13 illustrates the major heat losses in stoker-boilers. This section of the manual describes the major heat losses and explains how to reduce them. First, however, we will show you how boiler efficiency is determined by the measurement of heat losses.

CONSERVATION OF ENERGY

On of the laws of nature states that energy is conserved. It may change form, as from chemical energy to thermal energy, but you always end up with as much as you started with. So in a coal fired stoker-boiler, if you add up the energy in the steam, the energy in the flue gas, the energy radiated from the boiler and all the other forms of energy leaving the boiler, they will exactly equal the energy in the coal burned. Another way of stating it is like this:

Energy in Coal = Energy in Steam + Energy in Heat Losses

BOILER EFFICIENCY

Boiler efficiency is the percentage of the coal's energy which is converted to steam energy. The most accurate way of determining boiler efficiency in stoker-boilers is to use what is known as the heat loss method. (Ref #16) In this method you simply measure the individual heat losses (expressed as percent of heat input) and subtract them from 100%. This is possible because energy is conserved.

Boiler Efficiency = 100% - Heat Losses

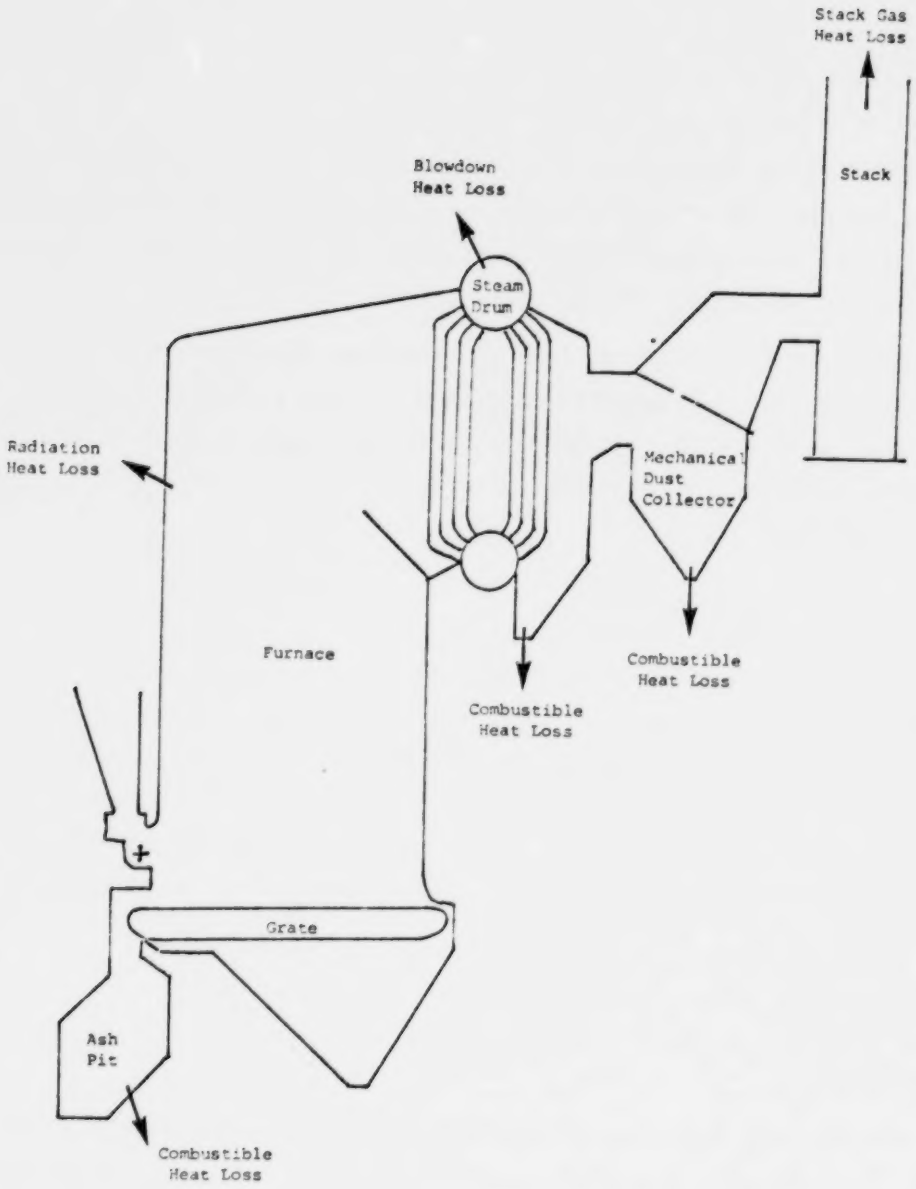

Figure 13. Major Heat Losses in Stoker Boilers

STACK GAS HEAT LOSS

The largest loss of energy in a stoker-fired boiler is the energy in the flue gas going out the stack, which might account for as much as 30% of the fuel input in the worst cases. This is called the stack gas heat loss. When engineers measure this heat loss, it is broken down into three components. These components are heat loss due to dry gas, heat loss due to moisture in the fuel, and heat loss due to H_2O from the combustion of H_2. As far as the operator is concerned, these three can all be lumped into one category: stack gas heat loss.

The biggest gains in boiler efficiency can be obtained by minimizing the stack gas loss. This loss depends on the temperature and the volume of gas leaving the boiler, so a reduction in either one of these will reduce the heat loss.

The practical minimum flue gas temperature limit is about 300°F. At lower temperatures, sulfuric acid vapor in the flue gas condenses on cold metal surfaces and causes severe corrosion. Therefore, some stack gas heat loss is unavoidable. To eliminate the stack gas heat loss altogether, you would have to reduce the stack gas temperature to the temperature of the air around the boiler. Practically speaking, this is impossible.

There are three basic strategies for minimizing the stack gas heat loss. They are:

1. Minimizing excess air
2. Keeping heat transfer surfaces clean
3. Adding flue gas heat recovery equipment where justified

When excess air is reduced, it reduces the volume of flue gas leaving the boiler. It also reduces the temperature of the flue gas because the gas velocities are reduced and the flue gas spends more time in the boiler where heat can be absorbed. As a result of reducing the volume and temperature of the flue gas, the stack gas heat loss is reduced and the boiler efficiency is increased. As a rule of thumb, boiler efficiency can be increased one percent for each 15 percent reduction in excess air, 1.3% reduction in O_2, or 40°F reduction of stack gas temperature. What is one percent of your annual fuel bill?

Keeping heat transfer surfaces clean must also be considered when operating the boiler. Ash deposits on water walls (slagging) and on boiler tubes (fouling), and scale deposits on the waterside tube surfaces act as insulation. This reduces the amount of heat the boiler water absorbs from the flue gas. As a result, the flue gas temperature is high and the boiler efficiency is low. Fouling and slagging are controlled by proper use of soot blowers, overfire air and excess air. Scale deposits are controlled by feedwater treatment and proper use of blowdown.

The third strategy for minimizing stack gas heat loss is to install additional heat recovery equipment such as an air heater or economizer. If the boiler's flue gas temperature is greater than 450° when tuned-up, it is worthwhile considering one of these devices. An engineering study will be required to determine if such a device will be cost-effective on your boiler.

COMBUSTIBLE HEAT LOSS

The second largest heat loss in stokers is due to unburned fuel. This is called the combustible heat loss, and is often greater than 5% of the coal's energy. It occurs in three major ways:

1. Carbon in the bottom ash
2. Carbon in the flyash
3. Combustible gases in the flue gas

Carbon in the bottom ash results when coal is dumped into the ash pit before it has been completely burned. The operator should take care to adjust the stoker so that the carbon is completely burned out. On traveling and chain grate stokers, this is done by properly adjusting the coal gate position, grate speed, and the undergrate air flow. On spreader stokers, the operator must adjust the grate speed, undergrate air flow, and the coal feeders if necessary. Experience will show which stoker adjustments work best.

Recent tests on 18 stokers gave the following range of heat losses due to combustibles in the bottom ash: (Ref #1-12)

Heat Loss Due to Combustibles in the Bottom Ash, Percent

	Lowest	Highest	Average
Spreader Stokers	0.0%	3.4%	0.9%
Overfeed Stokers	0.4%	8.1%	2.4%
Underfeed Stokers	1.2%	3.9%	3.2%

Carbon in the flyash is the result of small coal particles being blown off the grate or, in the case of spreader stokers, small particles being caught up (or entrained) in the gas flow before they land on the grate. This is also called flycarbon, carbon carryover, or combustibles in the flyash. To reduce this heat loss, you must reduce the particulate loading. Increasing the overfire air has been found to be effective in some cases. Reducing the excess air may also work in some cases. And, a coal with fewer fines or less ash may help.

Tests on 18 stokers gave the following range of heat losses due to combustibles in the flyash: (Ref #1-12)

Heat Loss Due to Combustibles in the Flyash

	Lowest	Highest	Average
Spreader Stokers	0.5%	9.2%	4.4%
Overfeed Stokers	0.3%	1.1%	0.5%
Underfeed Stokers	0.1%	0.2%	0.1%

Combustible gases are volatiles which did not burn to completion. The most commonly measured combustible gas is carbon monoxide (CO). Carbon monoxide is formed when the excess air is too low in some area of the grate, or when the flame impinges on a cold water wall. If the coal is evenly distributed on the grate, and if the undergrate air and overfire air are properly adjusted, this heat loss is minimized. On most stokers, the carbon monoxide concentration can be maintained below 400 ppm (.04%). This is about a .2% heat loss.

RADIATION HEAT LOSS

Some of the heat of combustion escapes through the walls of the furnace without being absorbed by the boiler water. This energy loss is called the radiation heat loss. Some radiation heat loss is unavoidable. If there were none, the outside surfaces of the stoker-boiler would be the same temperature as the surrounding air. Most stoker-boilers are properly insulated when installed. It is necessary to maintain the insulation in good condition. This includes all hot surfaces: water walls, ducting upstream of heat recovery devices, and steam pipes.

A properly insulated boiler has the following radiation heat losses at full load.[16] Note that larger boilers lose a smaller fraction of their heat through radiation from hot surfaces.

	Radiation Heat Loss
200,000 lb/hr boiler	.5%
100,000 lb/hr boiler	.7%
50,000 lb/hr boiler	.9%
20,000 lb.hr boiler	1.0%

BLOWDOWN HEAT LOSSES

There are other heat losses, but they are usually quite small. One worth mentioning, however, is blowdown. A certain amount of blowdown is necessary to maintain control of dissolved solids in the boiler water. Excessive blowdown, however, is a heat loss because it is energy being thrown away. One way to reduce this heat loss is to install a continuous blowdown heat recovery device. These devices are now economical for blowdowns as low as 500 lb/hr. The other way to minimize blowdown heat loss is to establish a good feedwater treatment program and to check the dissolved solids level regularly. In this way you can reduce the amount of blowdown required.

SUMMARY

All of these heat losses taken together add up to between 15% and 35% of the coal's energy. An operator can usually save enough on fuel bills to cover his salary by understanding these heat losses and operating the stoker-boiler at peak efficiency.

SECTION 5

GUIDELINES FOR CLEAN AND EFFICIENT BOILER OPERATION

This section discusses ways in which an operator can obtain peak boiler efficiency from his stoker-boiler while maintaining pollutant emissions within allowable limits. The material in this section does not replace the manufacturers operating instructions, but supplements it. Always use common sense when applying these, or any, guidelines.

BOILER MAINTENANCE

At most of the larger installations, the boiler-operator is not responsible for performing maintenance tasks. However, he is always responsible for reporting problem areas requiring maintenance. The following are common problem areas which directly affect boiler efficiency.

Undergrate Air Distribution

For peak efficiency the undergrate air must be properly distributed to the coal. Replace worn, broken, or warped grate sections. Replace worn air seals which allow undergrate air to short circuit the grate. Repair or replace undergrate air zone dampers which prevent proper control of the air distribution. Finally, repair the coal feed mechanism if it does not distribute an even bed of coal to the grate.

Air Infiltration

For peak efficiency, air infiltration to the furnace must be minimized. The boiler economizer and air heater casings should be tight, with no air leaks. Seals between the stoker and the boiler must be tight. Replace warped or cracked access doors which do not seal properly. Replace missing sight glass in view ports, patch leaks in ductwork, especially when upstream of an air heater or economizer.

Insulation

Considerable energy is wasted if hot surfaces are not properly insulated. For example, the heat loss from 100 feet of bare 2-inch pipe carrying saturated steam at 150 psig is equivalent to a fuel loss of one ton of coal every 12 days. If that were 12-inch pipe and 250 psig, the fuel loss would be one ton of coal every 2 days. Repair damaged or missing insulation and refractory on all hot surfaces.

Steam Leaks

An obvious waste of energy results from the numerous steam leaks at pipe joints, flanges, valves and unions. Less obvious are the steam losses from malfunctioning steam traps. It pays to repair steam leaks as soon as possible.

Soot Blowers

Soot blowers should be checked for proper operation. If ash deposits are allowed to accumulate on boiler tubes, less of the coal's heat will make steam and more will be lost out the stack. It has been said that 1/8 inch of soot equals one inch of insulation.

Instrumentation and Controls

Pressure gauges, draft gauges, temperature indicators and flow indicators are the eyes of the operator into the stoker-boiler. These should be routinely calibrated and serviced.

Boiler controls are required to maintain optimum firing conditions. If the controls are not working properly, the boiler's efficiency will suffer. Check controls for proper movement of valves, excessive play in linkages, adequate instrument air pressure, regulators, unnecessary cycling of firing rate, and proper operation of all safety interlocks and boiler trip circuits.

THE OPERATORS'S LOG

It is the operator's responsibility to maintain a complete log of panel board data and significant events. This data is used by the plant engineer to detect deterioration in stoker-boiler performance. For example, if the stack

gas temperature creeps upward with time, it may mean a slagging or fouling problem, or a problem with the excess air. Other trends may indicate other problem areas requiring attention. The number of items on the log sheet and the frequency with which they are recorded depends on the size and complexity of the boiler. Figure 14 illustrates a high pressure boiler log sheet for recording twice daily readings. Figure 15 illustrates a log sheet for recording hourly readings.

Whatever size the boiler, the most important efficiency-related items to record are the steam flow, flue gas temperature, and excess air. It is highly recommended that all boilers be equipped with a stem thermometer or thermocouple for measuring flue gas temperature after the last heat recovery device. It is also recommended that an oxygen monitor or carbon dioxide monitor be installed for determining excess air. These devices will quickly pay for themselves in energy savings.

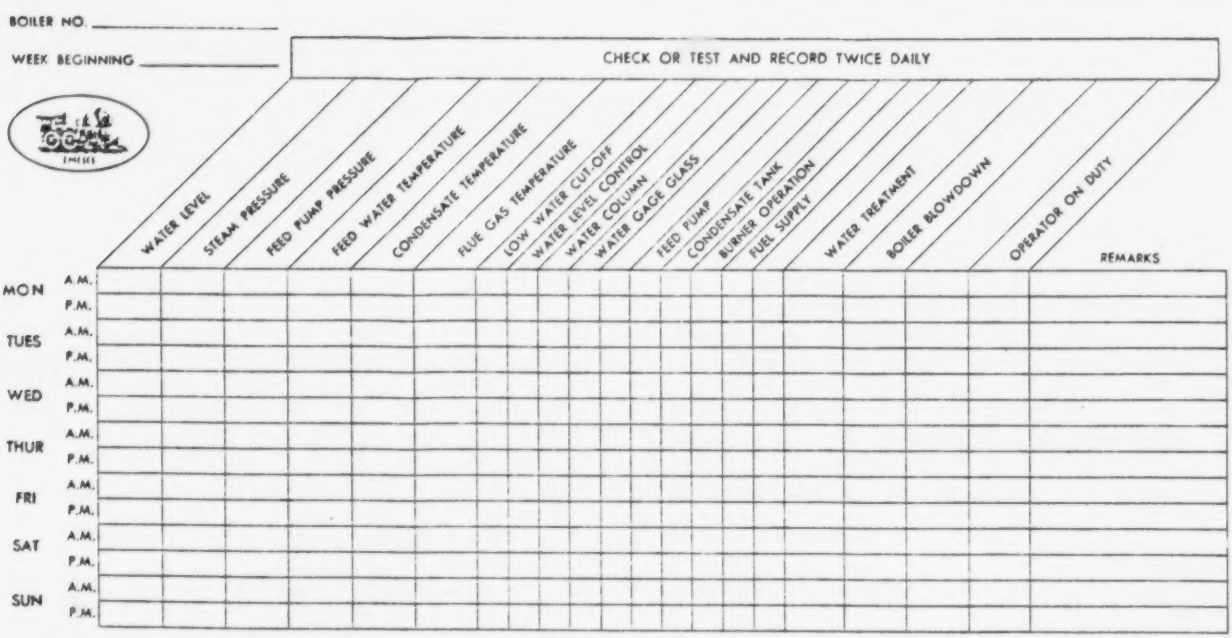

Figure 14. High Pressure Power Boiler Log Sheet for Twice Daily Readings (Compliments of the Hartford Steam Boiler Inspection and Insurance Company).

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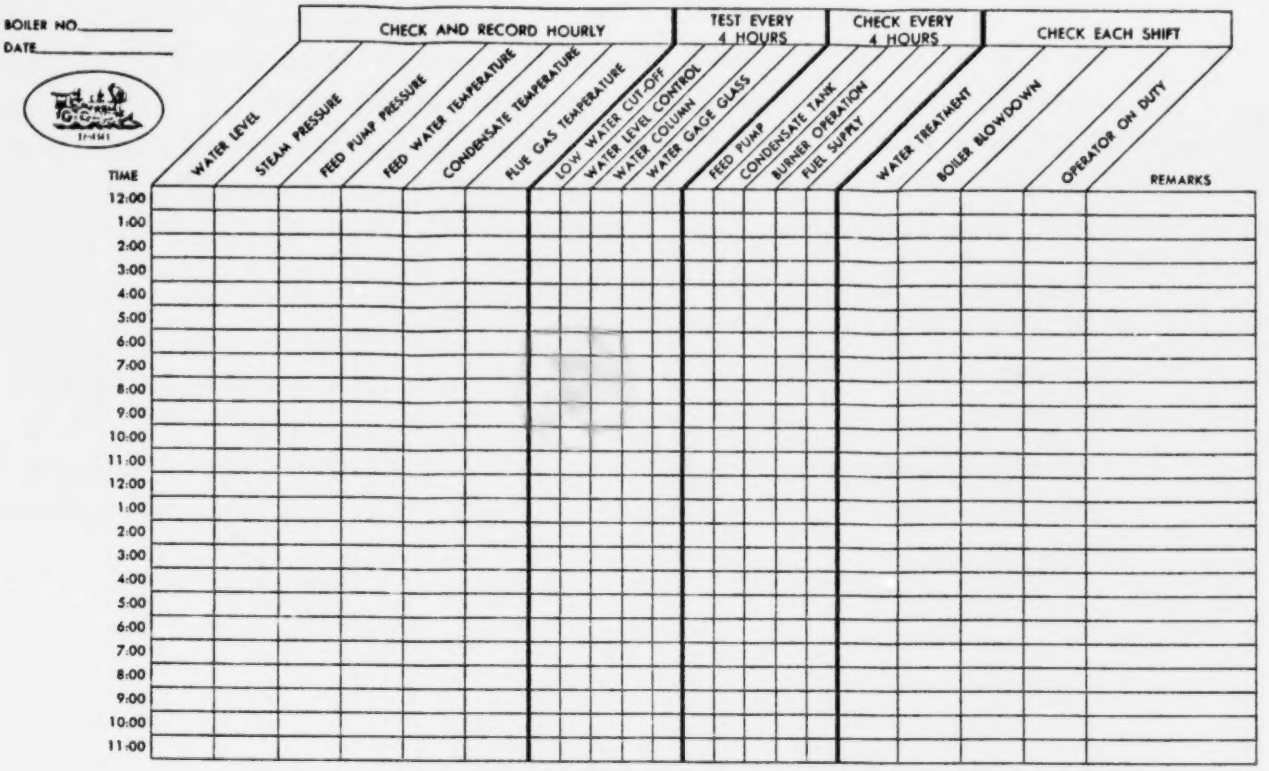

Figure 15. High Pressure Boiler Log Sheet for 24-Hourly Readings (Compliments of the Hartford Steam Boiler Inspection and Insurance Company).

OPTIMIZING THE EXCESS AIR

Optimizing the excess air is the easiest way to make substantial improvements in boiler efficiency. All that is required is some initiative on the part of the operator, and the appropriate instruments for monitoring excess air, incomplete combustion and stack gas temperature. Careful observation and thoughtful action can provide efficiency increases on the order of one-to-four percent.

Optimum excess air is illustrated in Figure 16. When excess air is reduced on a stoker, the stack gas heat loss drops until a point is reached where there is no longer enough oxygen for complete combustion. At this point there is a rapid increase in smoke and carbon monxide, often accompanied by severe clinkering. The excess air levels at which the smoke and CO begin to increase rapidly are called the "smoke limit" and the "CO limit". This point is the minimum

excess air level and is the most efficient place to operate. Unfortunately, to operate here is to flirt with disaster. The excess air could easily swing below the smoke and/or CO limit.

Therefore, the operator must allow for a safety margin in the excess air level so that normal swings in the load, coal sizing, or coal segregation do not produce undesirable firing conditions. The size of the margin is determined by trial and error, and depends on how stable the load is, and how sophisticated the combustion controls are. The safety margin typically ranges from 5% to 20% excess air (0.5-1.5% O_2). The optimum excess air is then established at this point. The optimum excess air must be re-established at several different firing rates. This is because more excess air is required at reduced loads than at full load.

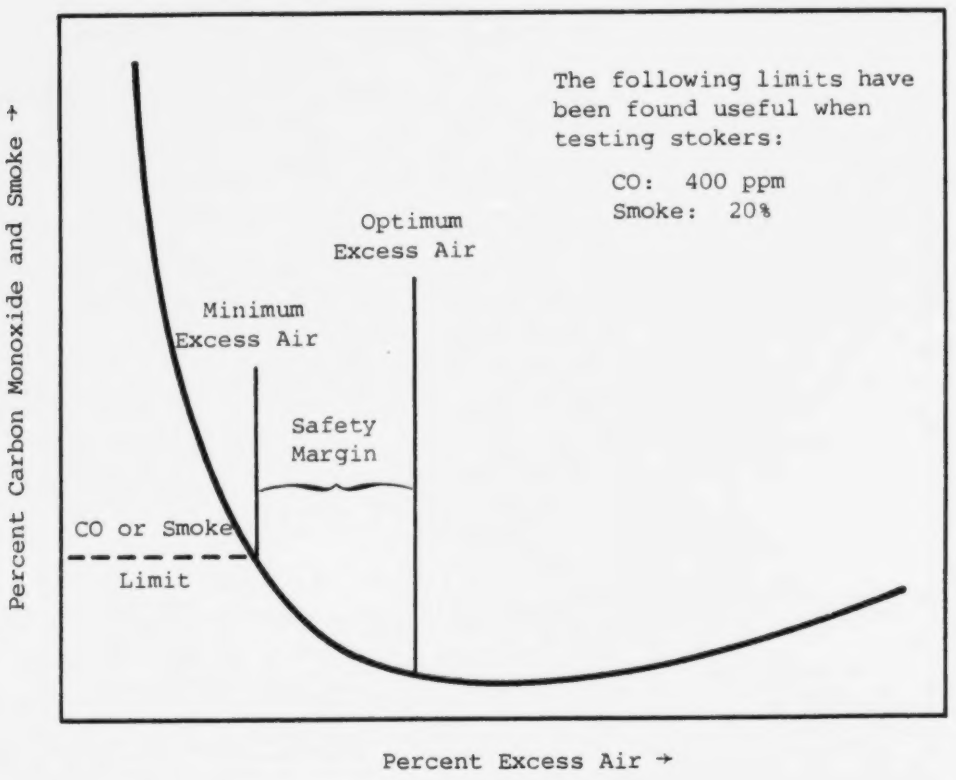
The following limits have been found useful when testing stokers:
CO: 400 ppm
Smoke: 20%
Optimum Excess Air
Minimum Excess Air
Safety Margin
CO or Smoke Limit
Percent Carbon Monoxide and Smoke →
Percent Excess Air →

Figure 16. Carbon Monoxide and Smoke vs Excess Air. This Figure Illustrates the use of a Safety Margin to Set an Optimum Excess Air Level.

Measurement Techniques

To tune the boiler for optimum excess air, three basic measurements are required. They are:

1. O_2 or CO_2 for determining operating excess air levels.
2. CO and visual observations for detecting the minimum excess air limit.
3. Stack gas temperature for determining the stack gas heat loss.

Excess air can be determined from Figure 17 if you know either the percentage of oxygen (O_2) or the percentage of carbon dioxide (CO_2) in the flue gas. Portable electronic and chemical analyzers are available for making these measurements at low cost if you are not already so equipped.

An alternate method for determining excess air is given in Figure 18. This chart is especially useful when using an Orsat-type analyzer where O_2, CO_2, CO, and N_2 are all determined simultaneously. On this chart, excess air is equal to "total air" minus 100%.

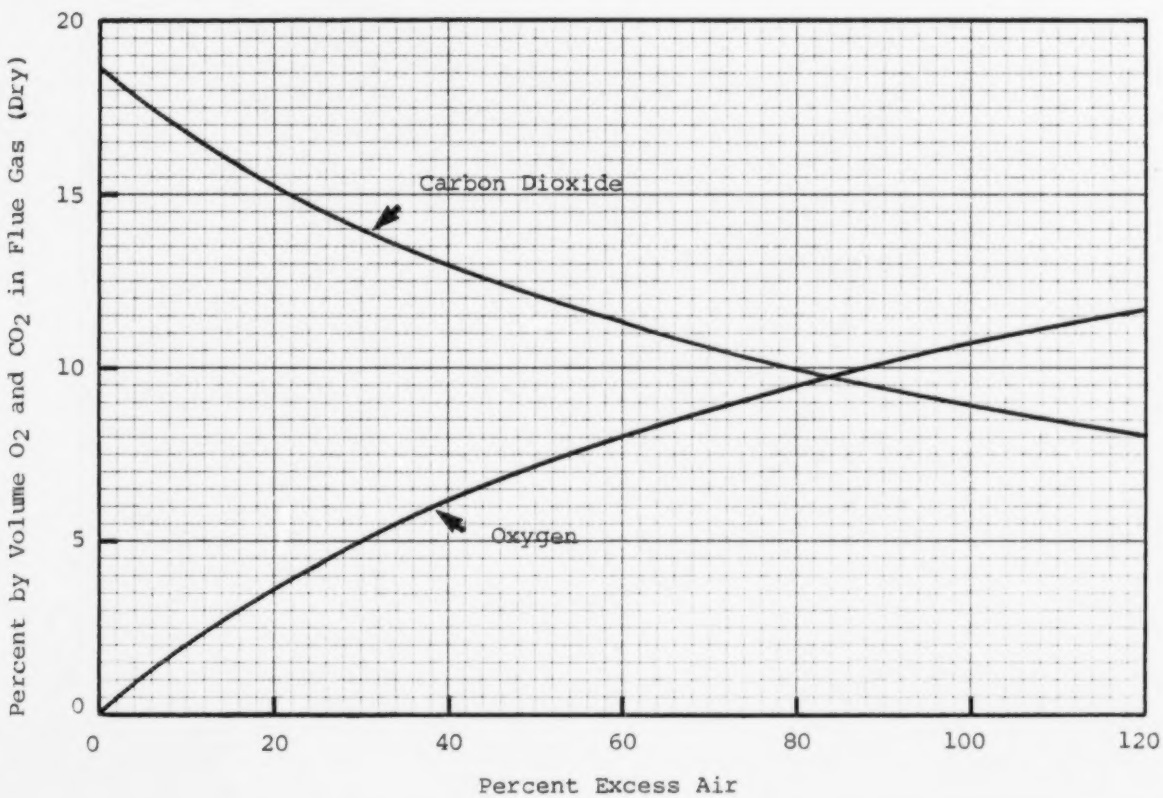

Figure 17. Combustion Chart for Determining Excess Air from either Flue Gas Oxygen or Carbon Monoxide (Dry Basis) while Firing a Bituminous Coal.

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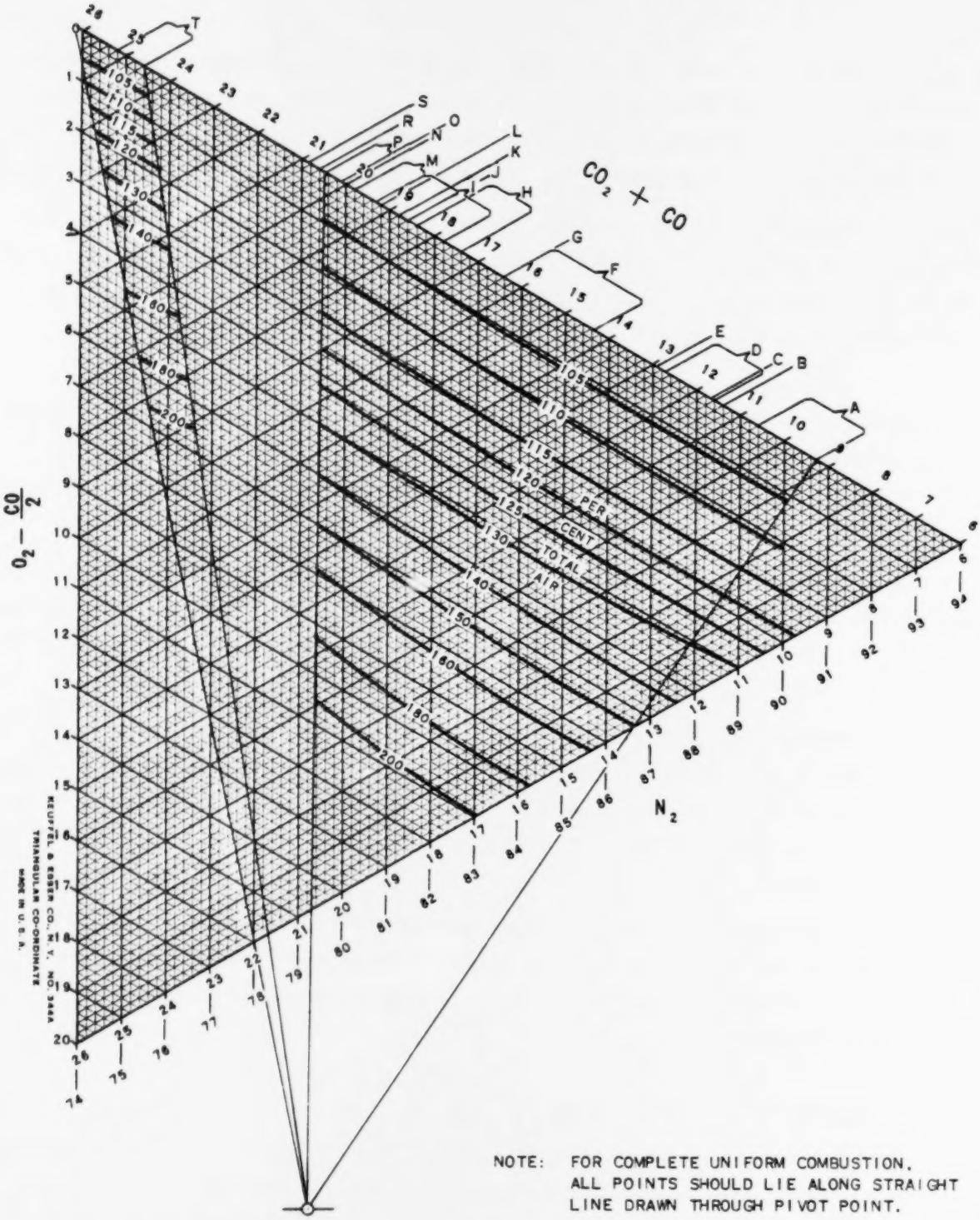
$CO_2 + CO$
$O_2 - \frac{CO}{2}$
N_2
PER CENT TOTAL AIR
NOTE: FOR COMPLETE UNIFORM COMBUSTION, ALL POINTS SHOULD LIE ALONG STRAIGHT LINE DRAWN THROUGH PIVOT POINT.

Figure 18. Combustion Chart for Determining Total Air from an Orsat Flue Gas Analysis. Data from Bituminous Coal Firing Should lie on a Straight Line drawn through Pivot Point and the Area Bracketed by "I" at the Top. (Reprinted with Permission of Keuffel & Esser Company, Morristown, New Jersey 07960)

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Carbon monoxide (CO) can be measured with an Orsat-type analyzer down to about 0.1%. However, this is not sensitive enough for an accurate determination of the minimum excess air limit. If at all possible, use an analyzer with a minimum detection limit of at least 0.01%, or 100 parts-per-million (ppm).

Visual observations include clinkering and slagging tendencies in the furnace, and smoke at the stack. If the stack is not equipped with an operating smoke meter for measuring opacity, it may be helpful to use a Ringlemann chart to determine the opacity.

Location of the flue gas sampling site can be as important as the selection of the proper measurement device. On negative-draft boilers, it should be upstream of the air preheater, if one is installed, or upstream of any known air leaks. This is because air leakage into the gas ducts can dilute the flue gas and resultant measurements won't give a true indication of furnace conditions.

Sample locations immediately downstream of bends, dampers, or induced-draft fans should be avoided. Gases in such areas can stratify or form pockets, leading to errors, especially when samples are withdrawn from a single point in the duct.

When a single-point sample probe is to be used, compare readings at several points in the duct first, to find the most representative probe location. When existing ports are not satisfactory, drill or cut out new ports. Remember, unless truly representative samples are obtained, your testing program will be of little value.

Flue gas temperatures are also subject to stratification in ducts, and a representative location for thermometers or other temperature sensors should be verified by trying several locations. Consult the boiler manufacturer for recommended location.

Efficiency Improvement Procedures

The boiler should be inspected prior to determining the optimum oxygen operating level. The various items to check are summarized above in the subsection entitled "Boiler Maintenance". The boiler manufacturer should be consulted for a more complete list reflecting your particular equipment.

Once the boiler has been inspected and is in good mechanical condition, the step-by-step procedures for minimizing flue gas oxygen may begin. The procedure is as follows:

STEP-BY-STEP PROCEDURES FOR MINIMIZING FLUE GAS OXYGEN

1. Bring the boiler to the test firing rate and put the combustion controls on manual. Make sure all safety interlocks are functioning properly.

2. After stabilizing, observe flame conditions and take a complete set of readings (O_2 or CO_2, stack gas temperature, CO and/or opacity).

3. Increase air flow to the furnace by about 1% O_2 allowing time to stabilize. Then take another set of readings.

4. Reduce the air flow in small steps while observing stack and flame conditions. Allow the unit to stabilize following each change and record the data.

5. Continue to reduce the air flow until a minimum excess air condition is reached as indicated by smoke, a sudden rise in CO, or other visible deterioration in conditions.

6. Establish a safe margin in excess air above the minimum and reset the combustion controls to maintain this "optimum" level.

7. Develop a CO or smoke versus excess air characteristic curve similar to Figure 16 using the data obtained from the test.

8. Compare the minimum excess air value to the predicted value provided by the stoker and/or boiler manufacturers. High excess air levels should be investigated (see the paragraphs entitled "Boiler Maintenance" and "Fine Tuning").

9. Repeat Steps 1-8 for each boiler load to be considered. Some compromise in optimum excess air settings may be necessary since control adjustments at one firing rate may affect conditions at other firing rates.

10. After these adjustments have been completed, verify the operation of these settings by observing normal load swings. If undesirable conditions are encountered, increase the safety margin.

The data obtained under Steps 2 through 5 will look something like that shown in the following table.

EXAMPLE OF EFFICIENCY IMPROVEMENT TEST DATA

		% O_2	CO, ppm	Stack Gas Temperature, °F
Step 2		8.9	105	472
Step 3		10.0	130	480
Step 4	(a)	8.3	95	463
	(b)	7.5	100	461
	(c)	6.8	158	456
	(d)	6.0	270	450
	(e)	5.2	612	445
Step 5		4.8	1050	442
Step 6		6.6	180	455

In this example, the baseline or as-found O_2 was 8.9%. The air flow was first raised and then lowered in steps until carbon monoxide exceeded 1000 parts per million. As the test proceeded, the carbon monoxide data were plotted as a function of O_2 as shown in Figure 19.

The carbon monoxide limit is taken to be 400 ppm. Therefore, the minimum flue gas oxygen operating level is 5.6%. If we select a 1% oxygen safety margin, then the optimum oxygen operating level is 6.6%. We adjust the boiler controls to maintain this oxygen level and record one more set of data as shown in Step 6 of the above table.

Next, we compare our operating level with that recommended by the stoker-boiler manufacturer. We note that they recommend 40% excess air. Referring back to Figure 17, we see that 40% excess air is about 6.2% O_2. This is reasonably close to the optimum operating level we determined by test, and we are now satisfied that our boiler is operating as it should. Step 8 is now complete.

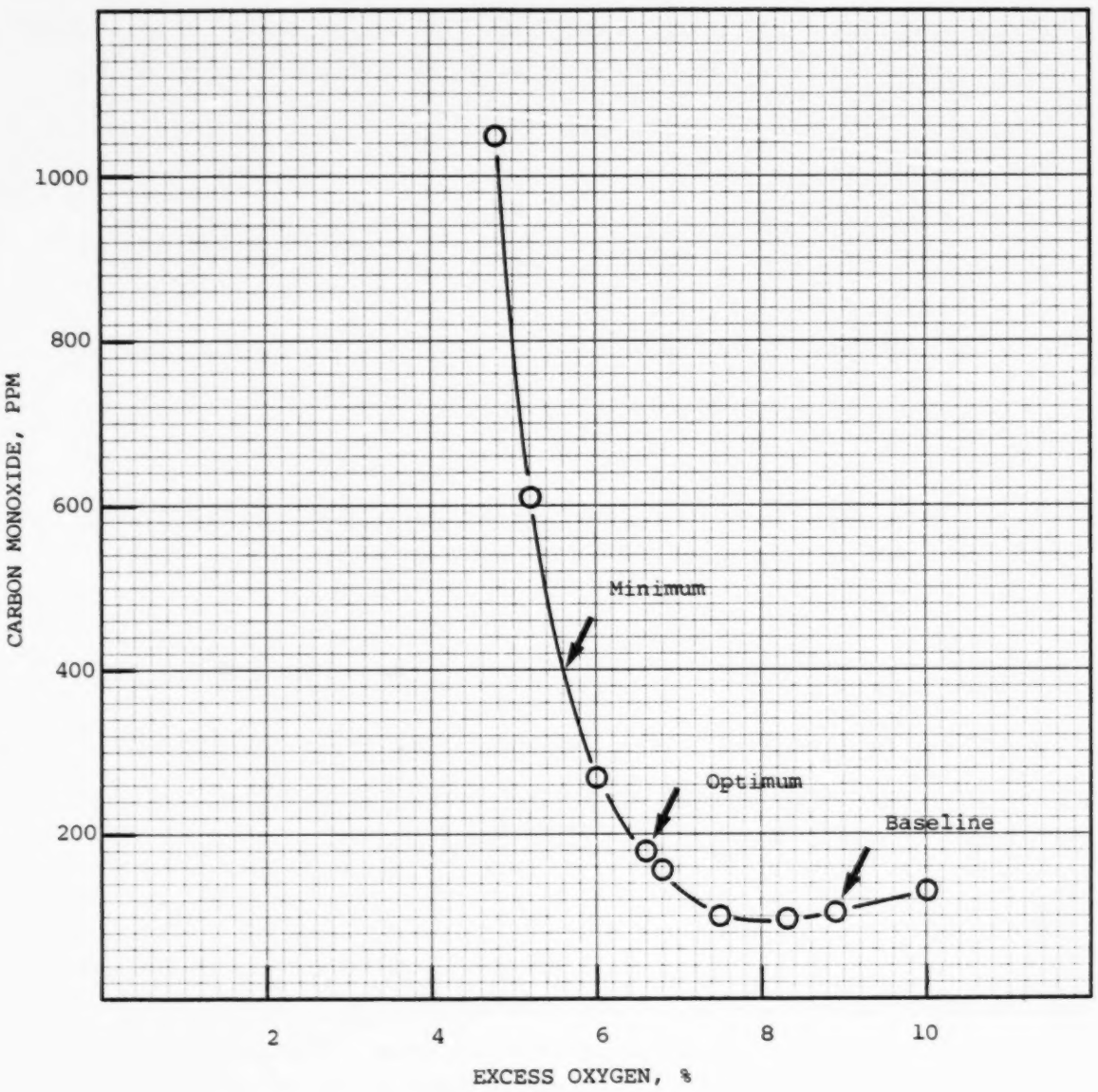

Figure 19. This is a Plot of the CO - O_2 Data Given in the Example

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To find out how much we improved the boiler efficiency, we refer to Figure 20. This plot relates stack gas O_2 and stack gas temperature to stack gas heat loss for a typical bituminous coal. It may be used with most coals to find approximate stack gas heat loss savings. Using this plot we obtain the following results:

	O_2, %	Stack Gas Temperature, °F	Stack Gas Heat Loss From Figure 20
Baseline Test	8.9	472	17.8%
Optimum Test	6.6	455	15.1%
		EFFICIENCY GAIN	2.7%

To obtain the percent savings in the annual fuel bill, we divide the efficiency gain by the boiler efficiency and multiply by 100.

$$\frac{\text{2.7 Efficiency Gain}}{\text{80\% Boiler Efficiency}} \times 100\% = 3.38\% \text{ Fuel Savings}$$

If the annual fuel bill is $1,000,000 per year, then the cost savings is $33,800 annually. Each situation will differ, but in all cases, it is well worth the effort to minimize the excess air.

Fine Tuning

If the optimum excess air level determined by test is higher than the manufacturers recommended level, the stoker should be re-examined. It is sometimes possible to lower the CO or smoke limit, thus allowing greater efficiency gains. The usual procedure involves one or more of the following actions:

1. Minimize coal segregation to the stoker.
2. Adjust stoker for uniform coal distribution on the grate.
3. Adjust stoker for balanced undergrate air flow through the grate.
4. Adjust overfire air to improve turbulence and hold flame front off the water walls.
5. Reduce the coal fines if they are excessively high.
6. Reduce air infiltration through cracks in the casing and access doors.

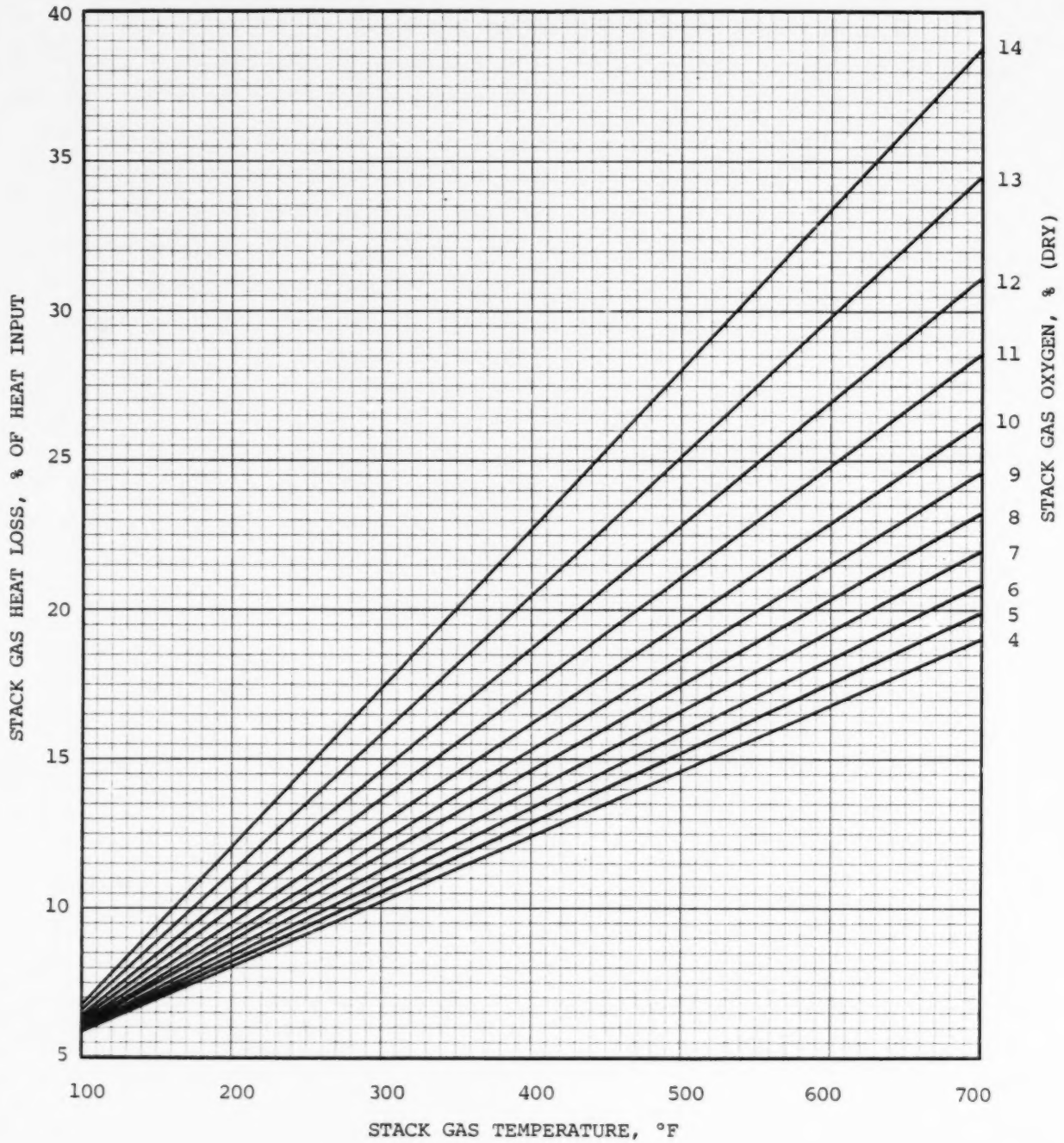

Figure 20. Stack Gas Heat Loss as a Function of Stack Gas Temperature and Stack Gas Oxygen for a Typical Bituminous Coal. (Coal Composition by Weight: H_2O-5%, C-73%, H-5%, N-1.4%, S-1.5%, O-7.1%, Ash-7%, 13,000 Btu/lb., Ambient Air Temperature - 80°F)

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Here is a true example of a boiler requiring fine tuning. It is a 182,000 lb/hr spreader stoker belonging to a midwestern pulp and paper company. The full load smoke limit on this unit was found to be at 50% excess air, yet the manufacturer claimed the unit was capable of operation at 30% excess air. Upon investigation, it was discovered that coal was being segregated in the hopper so that most of the coal fines were being fed to one section of the grate. As a result of this coal size segregation, the excess air was low in some areas of the grate and much higher in the other areas. The areas of low excess air reached the smoke limit long before the average excess air reached its design levels.

Maintaining Optimum Excess Air

It is easy to demonstrate optimum boiler efficiency during a test. It is much harder to maintain optimum efficiency day after day. Maintaining optimum boiler efficiency requires a conscientious effort by the boiler operators and their supervisors.

During the first month or two you should pay special attention to combustion conditions. Watch for problems with clinkering, smoke, excessive carbon monoxide and slag buildup. Check the excess air level and the stack gas temperature regularly. Take corrective action if conditions deteriorate. Keep on top of boiler maintenance requirements. Thoroughly inspect the boiler during the next shutdown.

One of the best aids an operator can have in maintaining low excess air is a stack gas sampling system which continuously monitors oxygen and, if possible, carbon monxoide or combustibles in the flue gas. There are several reliable O_2 and CO monitors on the market, and they will usually pay for themselves in fuel savings over a short period of time. If you don't use continuous monitors, the excess air level should be routinely checked with an Orsat, or other portable gas sampling device.

Normal Ranges of Excess Air

If you don't know what the design excess air level is for your stoker, you might be interested in some rule-of-thumb figures. Spreader stokers should be able to operate at or near 30% excess air at high firing rates. Other types

of stokers should be able to operate at or near 50% excess air. These are only general guidelines. Smaller stokers tend to require more excess air than larger ones, and the stoker's state of repair will make a difference. The quality of coal fired may also influence excess air requirements.

Recent tests on six spreader stokers and five mass-fired overfeed stokers produced the excess air operating levels shown in Figures 21 and 22. These trend lines represent average as-found levels and are not necessarily the optimum excess air levels. Note that in every case more excess air was required as the firing rate was lowered.

Similar profiles can be produced for your stoker for the optimum excess air levels at all firing rates by following the efficiency improvement procedures given earlier. They would be a very helpful guide to operators who have the means to measure the excess air. If O_2 or CO_2 is used on the plot instead of excess air, they will be more easily compared to the direct readings.

How Excess Air Effects Emissions

When the excess air is optimized, some pollutant emissions decrease. Thus, you obtain two direct benefits: Energy savings and cleaner stack gases. The emission which decreases the most is nitric oxide (NO), a pollutant which is responsible for producing photochemical smog among other things. Nitric oxide emissions drop by nearly 0.03 $lb/10^6$Btu for each 10% excess air drop. An example of this is shown in Figure 23.

Carbon monoxide emissions are usually lowest at the optimum excess air level. They increase slowly as the excess air goes up, and they increase rapidly as the excess air goes below the carbon monoxide limit.

Particulate emissions are sometimes improved and sometimes unchanged by reducing excess air. Reducing the excess air reduces the gas velocities in the furnace and ductwork, and this in turn should carry less particulate material off the grate and allow more particulate material to settle out before it is emitted from the stack.

Finally, sulfur oxide emissions (SOx) are unaffected by changes in the excess air. About 95% of the sulfur in the coal is converted to SOx no matter how you operate the stoker-boiler.

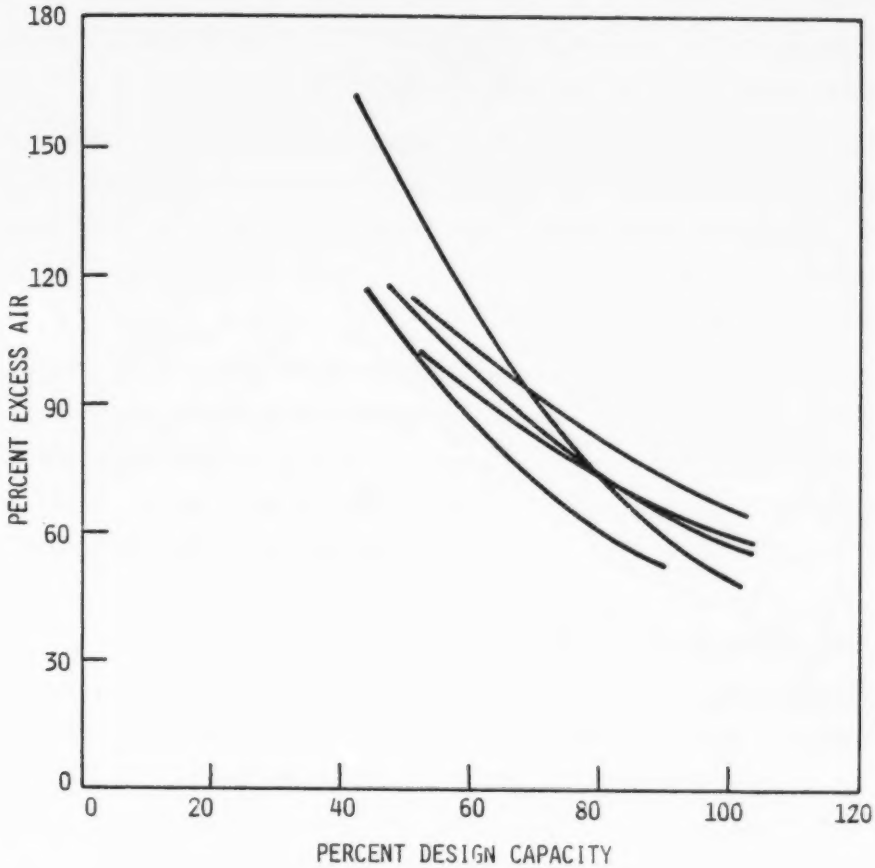

Figure 21. Excess Air Trends for Five Overfeed Stokers. The Trend Lines Represent Average Excess Air Levels Obtained over a Wide Range of Firing Rates. (Ref #4, 8, 9, 10, 11)

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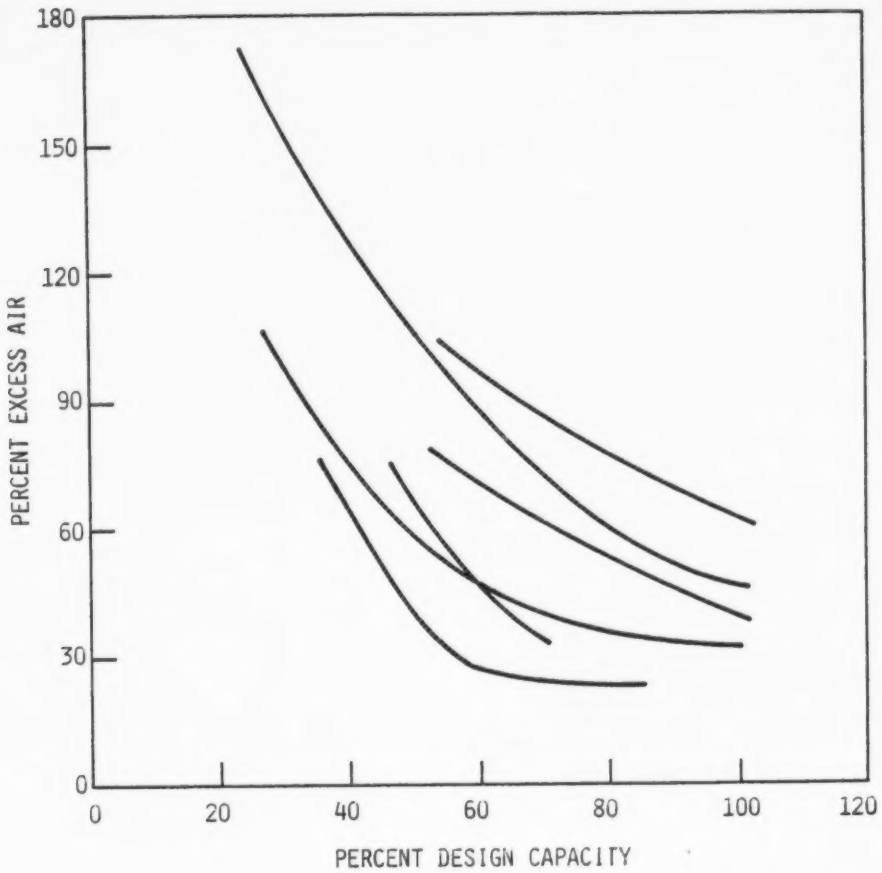

Figure 22. Excess Air Trends for Six Spreader Stokers Obtained over a Wide Range of Firing Rates. The Trend Lines Represent the Average of a Large Number of Tests. (Ref # 1, 2, 3, 5, 6, 7)

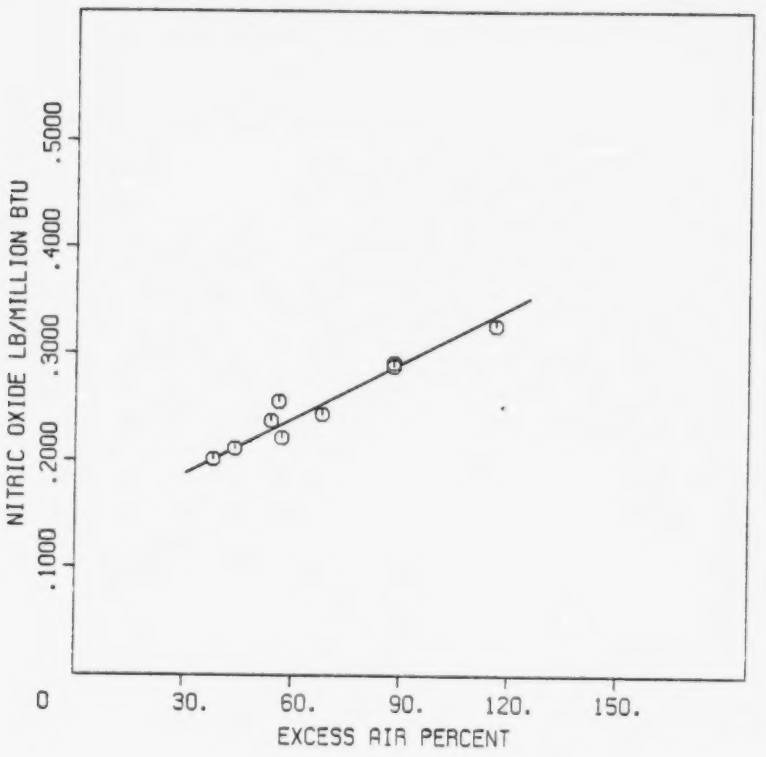

Figure 23. The Relationship Between Nitric Oxide and Excess Air on an Overfeed Stoker. (Ref #9)

OVERFIRE AIR

Overfire air has two main purposes in stoker-boiler operation. The primary purpose is to promote turbulence in the flame zone so as to mix the volatile gases with the air for better combustion. The secondary purpose is to hold the flames away from the water walls so as to prevent premature cooling or quenching of the flames. Recent tests have shown that increased use of overfire air can also reduce particulate emissions. An example of this effect is shown in Figure 24.

At high boiler loads, the overfire air should be set at a high level. Reduce the overfire air pressure at low boiler loads. If in doubt as to how much overfire air to use, you are usually better off to use more rather than less. When the overfire air is increased, allow the undergrate air to decrease so that the excess air remains low.

Whenever carbon monoxide or smoke are present, try increasing the overfire air pressure. This will sometimes clear up the problem and allow you to operate at a lower and more efficient excess air.

On some stokers, there may be a problem with high overfire air pressures if the resulting turbulence is lifting particulate matter off the grate. This is very rarely a problem, but when it does happen, the overfire air pressures should be reduced.

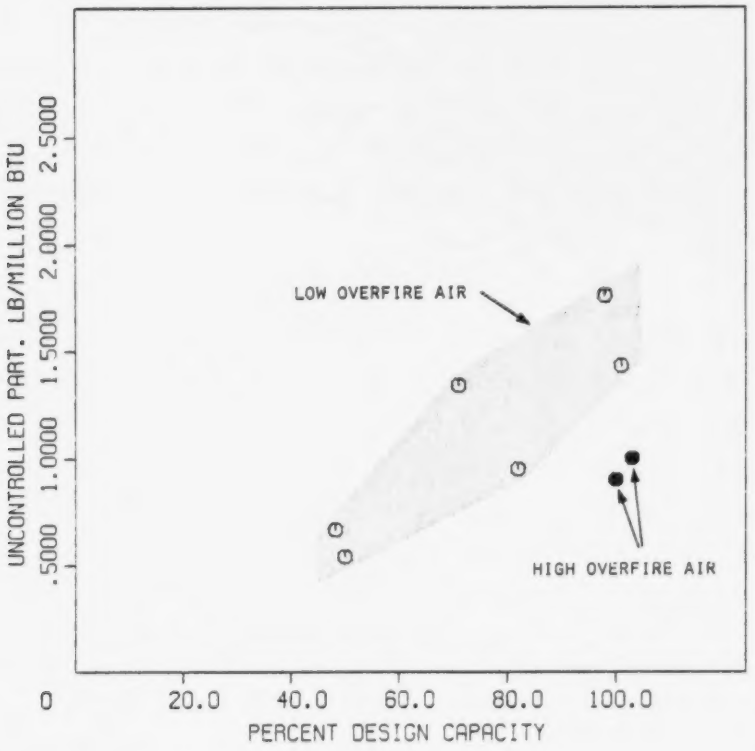

Figure 24. The Effect of Overfire Air Pressure on the Uncontrolled Particulate Loading on an Overfeed Stoker. (Ref. #9)

CINDER REINJECTION

Cinder reinjection, also known as flyash reinjection, is used primarily on spreader stokers. Its purpose is to recover some of the energy in the flyash by giving it a second chance to burn. The flyash from spreader stokers often contains 50-80% carbon and can account for more than 5% of the coal's energy. Incidentally, the percentage of carbon in the flyash of other types of stokers is much less, and the amount of flyash collected is less. Therefore, it's not worth installing cinder reinjection systems on non-spreader stokers.

On spreader stokers, the flyash collected in the boiler hopper is usually reinjected, and the flyash collected in the mechanical dust collector hopper and the economizer or air heater hopper is sometimes reinjected. The operator should insure that the reinjection lines do not plug up. If they do, they should be rodded open as soon as possible. Not only is energy wasted by plugged lines, but if the hoppers are allowed to fill up with ash, that ash will be blown out the stack and will increase the particulate emissions.

FIRING RATE

Most stokers are most efficient near full load. This is because stack gas heat losses are high at low loads where more excess air is required. Radiation heat losses are also higher at low loads. On the other hand, some stokers, when operated at their full firing rate, have high combustible heat losses due to high carbon carryover. On these units the efficiency drops off slightly at full load. As a rule-of-thumb, peak boiler efficiencies are obtained at about 80% of design capacity.

Some pollutant emissions also increase at high loads. Particulate loading typically increases with load as shown in Figure 25. If the load is unstable, as on swing load, particulate loading increases even more. Nitric oxide emissions generally stay at the same level at all firing rates on stokers, as do sulfur oxide emissions. Carbon monoxide emissions sometimes increase at full load, but they also increase at extremely low loads.

For the most efficient and the cleanest stoker operation, sudden load swings should be held to a minimum. When firing more than one boiler, the bulk of the load should be carried by the most efficient unit(s).

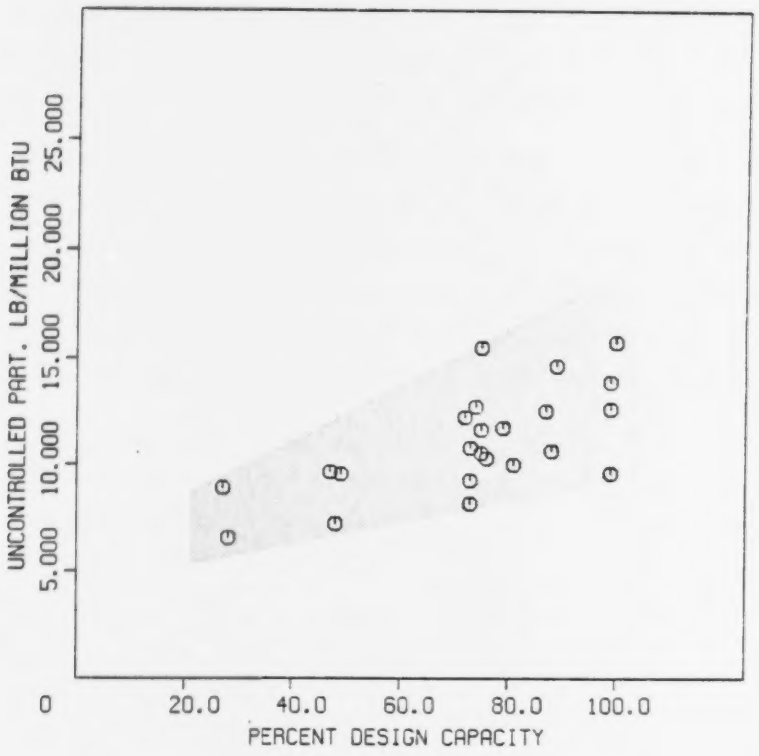

Figure 25. Uncontrolled Particulate Loading as a Function of Boiler Loading on a Spreader Stoker. (Ref. #2)

COAL PROPERTIES

Operators are generally not involved in obtaining coal supply contracts, so they don't need to be experts on all the coal properties. However, the operator is responsible for firing the purchased coal as efficiently and cleanly as possible, and for informing his supervisors of coal related problem areas.

There are several coal properties which have a direct effect on stoker-boiler emissions and efficiency. The operator should be aware of these properties.

Coal Ash

Coals which are higher in ash content tend to produce higher particulate emissions. This is only a generalization and it should not be assumed that the particulate loading is directly related to the ash content.

The type of ash makes a difference. In recent tests on a traveling grate overfeed stoker a washed coal and an unwashed coal from the same mine were fired in the stoker. The unwashed coal had 10% ash, but when washed the same coal had only 4% ash. In this case (Figure 26) there was a tremendous difference in particulate loadings because much of the ash in the unwashed coal was a clay-like material which was easily carried out of the furnace by the flue gas.

In tests on other stokers, coals with different ash contents were fired in the same stoker with very little or no change in particulate loading.

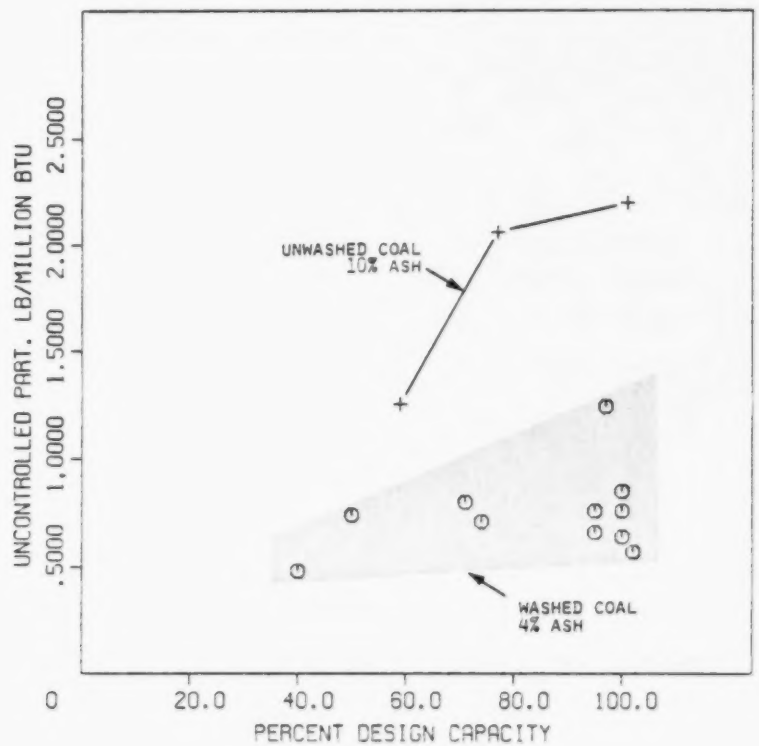

Figure 26. The Effect on Uncontrolled Particulate Loading of Washing a Coal to Reduce its Ash Content. Data are from an Overfeed Stoker. (Ref. #11)

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Coal Moisture

Coal has two forms of moisture. There is the inherent moisture which is a part of the coal, and there is surface moisture which is due to rain or conditions at the mine. You can't do anything about the inherent moisture, but the surface moisture can sometimes be avoided.

Coal moisture causes two problems. If excessive, it may make the coal hard to ignite, and it will always reduce the boiler efficiency.

Coal Sulfur

About 95% of the sulfur in the coal is converted during combustion to SO_2 and SO_3, commonly called SOx. The remaining 5% is retained in the ash. Therefore, by burning a lower sulfur coal you reduce your sulfur oxide emissions. Of course, there is another reason to burn a low sulfur coal, the sulfur emissions are very corrosive if they condense on exposed metal parts. The SO_3 instantly combines with water vapor (H_2O) to form sulfuric acid (H_2SO_4).

Coal Fines

The common definition of coal fines is the percentage of coal which passes through a 1/4" screen. Too many coal fines can lead to high particulate loadings because they are easily carried out of the furnace, and high combustible heat losses because the particulate matter carries carbon out of the furnace with it. High fines may also lead to severe clinkering problems.

When firing a high fines coal, make sure that the fines are evenly distributed on the grate, and are not segregated in one area only. The manner in which the coal is loaded into the hopper is important because it may lead to stratification.

A coal which was low in fines when it left the mine may be high in fines when it reaches the furnace because of all the handling it receives. Coals which break up and produce fines more easily than others are called highly "friable" coals. The American Boiler Mnaufacturers Association has published guidelines for the recommended size consistency of coal for firing in different types of stokers. These are presented in Figures 27, 28, and 29. Every attempt should be made to operate within these guidelines.

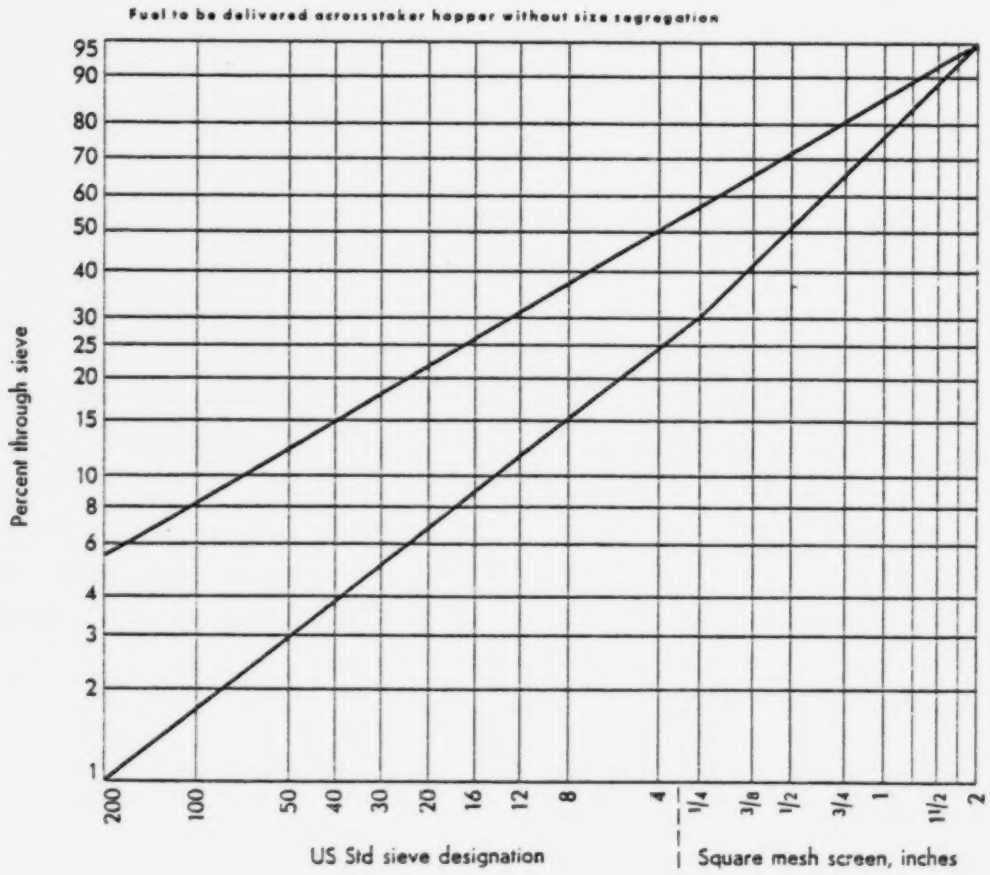

Figure 27. ABMA Recommended Limits of Coal Sizing for Underfeed Stokers.

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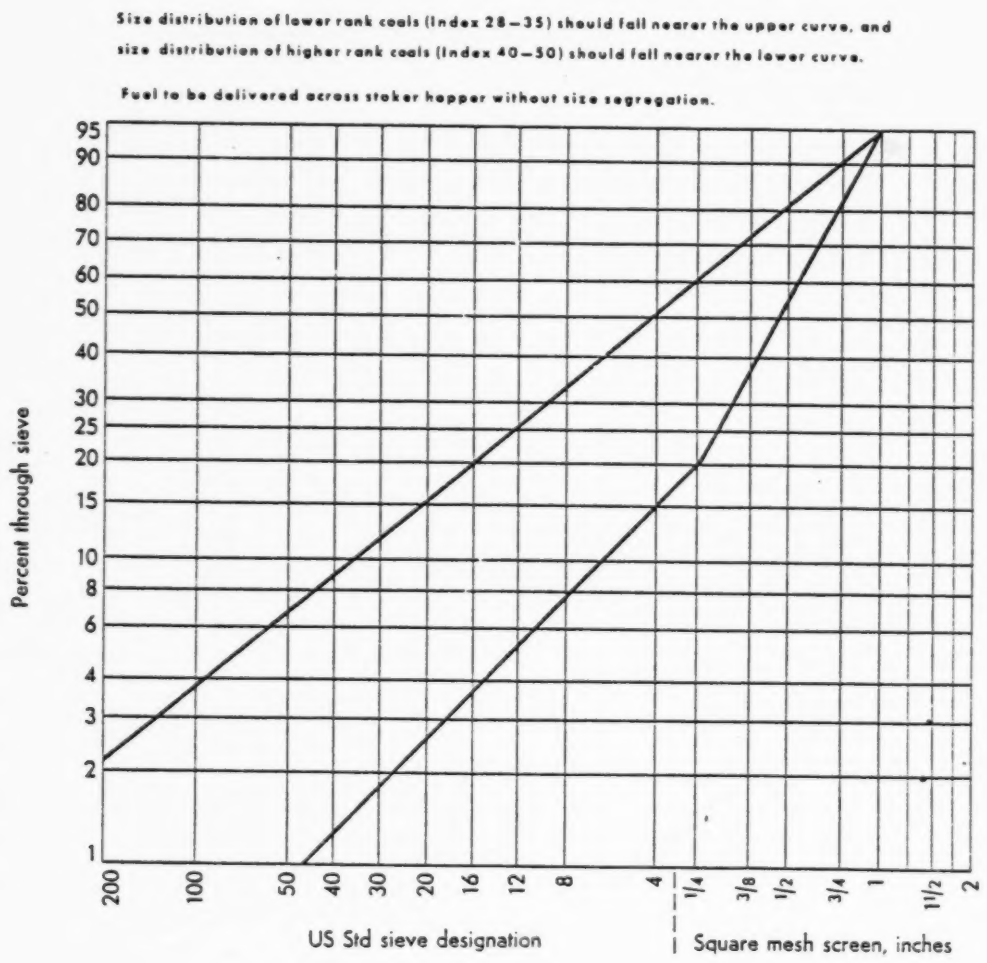

Figure 28. ABMA Recommended Limits of Coal Sizing for Overfeed Stokers.

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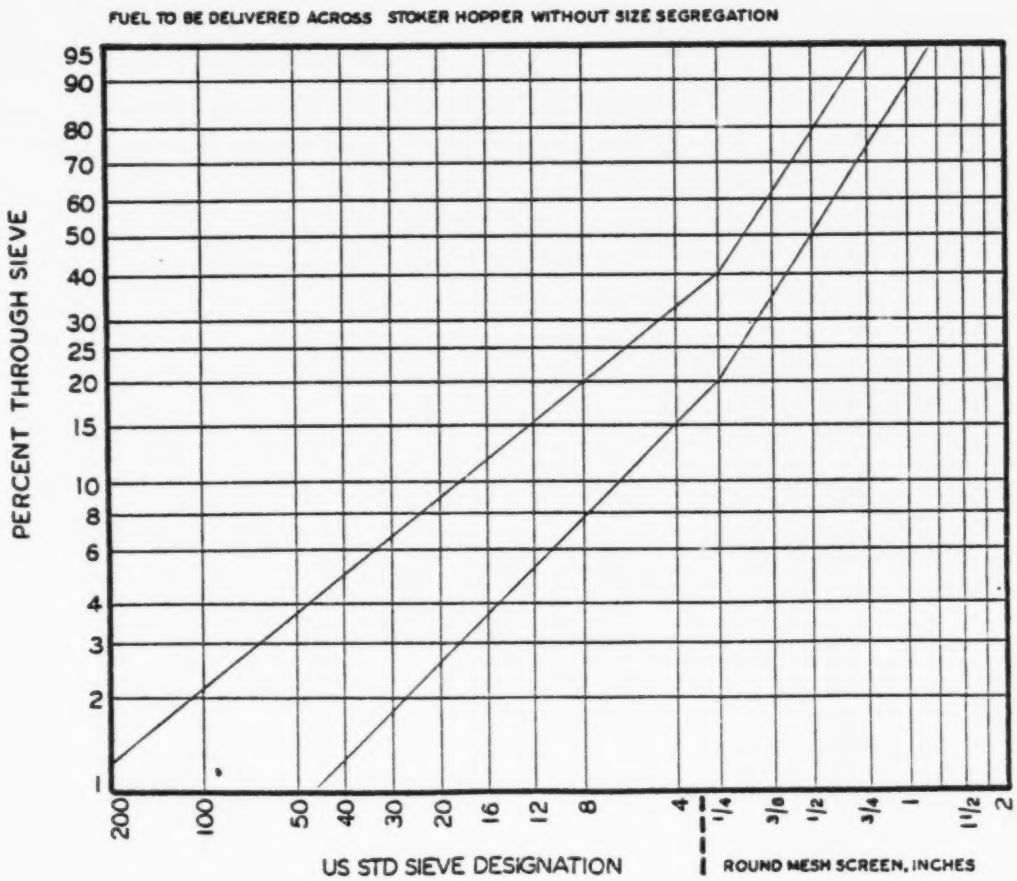

Figure 29. ABMA Recommended Limits of Coal Sizing for Spreader Stokers.

Ash Fusion Temperature

Some coals tend to clinker, slag and foul the boiler more than others. This is because the ash from these coals becomes sticky and begins to melt at lower temperatures. These coals have low ash fusion temperatures. Clinkering, slagging and fouling will decrease boiler efficiency by reducing the amount of heat absorbed by the boiler and increasing the stack gas heat loss. Firing a coal with a lower ash fusion temperature than that for which the boiler was designed can also lead to reduced boiler capacity, and it may require operation of the boiler at a higher and less efficient excess air level.

Free Swelling Index (FSI)

The free swelling index provides an indication of the caking characteristics of coal when burned on fuel beds. The caking characteristic of coal is the tendency of coal to melt together into a solid mass when rapidly heated. The free swelling index (FSI) is reported on a scale of 1 to 9 in increments of 1/2. Coals having a FSI from 1 to 3 are generally referred to as "free burning", from 3½ to 5 as moderately caking, and from 5½ to 9 as strongly caking. Caking characteristics have little or no effect on the performance of spreader stokers. However, free burning and moderately caking coals are preferred for overfeed stokers and underfeed stokers.

SUMMARY

The information presented in this document is meant to inform the operator of the various factors affecting coal stoker fired boiler emissions and efficiency over which he has control. It is meant to supplement his own experiences and the guidance provided by the boiler-stoker manufacturers.

It is hoped that this information will stimulate those in charge of coal stoker fired boilers to review their own maintenance and operating practices and to strive for improvements in their unit's efficiency and emissions. Remember that reducing the excess air alone can often save enough money to cover the operators salary. And, with the continued rise in fuel prices, the potential savings are growing larger each year.

If the reader is interested in more detailed information on the results of the American Boiler Manufacturers Association's extensive stoker test program, he may refer to the reports described in references 1 through 12. A final technical report summarizing the data from all of the above reports will be published by the U.S. Environmental Protection Agency soon after this document is released. The title of the final technical report will be "Emissions and Efficiency Performance of Industrial Coal Stoker Fired Boilers."

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1. Gabrielson, J. E., P. L. Langsjoen, and T. C. Kosvic. Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site A. EPA-600/7-78-136a, U.S. Environmental Protection Agency, Research Triangle Park, NC, July, 1978. 106 pp.

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APPENDIX A

CONVERSION FACTORS

ENGLISH AND METRIC UNITS TO SI UNITS

To Convert From	To	Multiply By
in	cm	2.540
in^2	cm^2	6.452
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	Kg	0.4536
lb/hr	Mg/s	0.1260
$lb/10^6Btu$	ng/J	430
g/Mcal	ng/J	239
Btu	J	1054
Btu/lb	J/kg	2324
Btu/hr	W	0.2929
J/sec	W	1.000
J/hr	W	3600
Btu/ft/hr	W/m	0.9609
Btu/ft/hr	J/hr/m	3459
$Btu/ft^2/hr$	W/m^2	3.152
$Btu/ft^2/hr$	$J/hr/m^2$	11349
$Btu/ft^3/hr$	W/m^3	10.34
$Btu/ft^3/hr$	$J/hr/m^3$	37234
psia	Pa	6895
$"H_2O$	Pa	249.1
Rankine	Celsius	C = 5/9R-273
Fahrenheit	Celsius	C = 5/9(F-32)
Celsius	Kelvin	K = C+273
Rankine	Kelvin	K = 5/9R

APPROXIMATE CONVERSION FACTORS FOR A TYPICAL COAL FUEL

ppm @ 3% O_2 (SOx as SO_2)	ng/J ($lb/10^6Btu$)	0.851 ($1.98x10^{-3}$)
ppm @ 3% O_2 (NOx as NO_2)	ng/J ($lb/10^6Btu$)	0.611 ($1.42x10^{-3}$)
ppm @ 3% O_2 (CO)	ng/J ($lb/10^6Btu$)	0.372 ($8.65x10^{-4}$)
ppm @ 3% O_2 (CH_4)	ng/J ($lb/10^6Btu$)	0.213 ($4.95x10^{-4}$)
g/Kg of Fuel	ng/J ($lb/10^6Btu$)	4300 (10)

APPENDIX B

CONVERSION FACTORS

SI UNITS TO ENGLISH AND METRIC UNITS

To Convert From	To	Multiply By
cm	in	0.3937
cm^2	in^2	0.1550
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
Kg	lb	2.205
Mg/s	lb/hr	7.937
ng/J	$lb/10^6Btu$	0.00233
ng/J	g/Mcal	0.00418
J	Btu	0.000948
J/kg	Btu/lb	0.000430
J/hr/m	Btu/ft/hr	0.000289
$J/hr/m^2$	$Btu/ft^2/hr$	0.0000881
$J/hr/m^3$	$Btu/ft^3/hr$	0.0000269
W	Btu/hr	3.414
W	J/hr	0.000278
W/m	Btu/ft/hr	1.041
W/m^2	$Btu/ft^2/hr$	0.317
W/m^3	$Btu/ft^3/hr$	0.0967
Pa	psia	0.000145
Pa	$"H_2O$	0.004014
Kelvin	Fahrenheit	F = 1.8K-460
Celsius	Fahrenheit	F = 1.8C+32
Fahrenheit	Rankine	R = F+460
Kelvin	Rankine	R = 1.8K

APPROXIMATE CONVERSION FACTORS FOR A TYPICAL COAL FUEL

ng/J	ppm @ 3% O_2 (SOx as SO_2)	1.18
ng/J	ppm @ 3% O_2 (NOx as NO_2)	1.64
ng/J	ppm @ 3% O_2 (CO)	2.69
ng/J	ppm @ 3% O_2 (CH_4)	4.69
ng/J	g/kg of fuel	0.000233

APPENDIX C

SI PREFIXES

Multiplication Factor	Prefix	SI Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto*	h
10^{1}	deka*	da
10^{-1}	deci*	d
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*Not recommended but occasionally used

APPENDIX D

EMISSION UNITS CONVERSION FACTORS FOR TYPICAL COAL FUEL (HV = 13,320 BTU/LB)

To Obtain \ Multiply By	% Weight in Fuel		lbs/10^6Btu		grams/10^6Cal		PPM (Dry @ 3% O_2)		Grains/SCF (Dry @ 12% CO_2)	
	S	N	SO_2	NO_2	SO_2	NO_2	SOx	NOx	SO_2	NO_2
% Weight In Fuel S	1		0.666		0.370		13.2×10^{-4}		1.48	
% Weight In Fuel N				0.405		0.225		5.76×10^{-4}		.903
lbs/10^6Btu SO_2	1.50		1		(.556)		19.8×10^{-4}		(2.23)	
lbs/10^6Btu NO_2		2.47				(.556)		14.2×10^{-4}		(2.23)
grams/10^6Cal SO_2	2.70		(1.8)		1		35.6×10^{-4}		(4.01)	
grams/10^6Cal NO_2		4.44		(1.8)				25.6×10^{-4}		(4.01)
PPM (Dry @ 3% O_2) SOx	758		505		281		1		1127	
PPM (Dry @ 3% O_2) NOx		1736		704		391				1566
Grains/SCF (Dry @ 12% CO_2) SO_2	.676		(.448)		(.249)		8.87×10^{-4}		1	
Grains/SCF (Dry @ 12% CO_2) NO_2		1.11		(.448)		(.249)		6.39×10^{-4}		

NOTE: 1. Values in parenthesis can be used for all flue gas constituents such as oxides of carbon, oxides of nitrogen, oxides of sulfur, hydrocarbons, particulates, etc.
2. Standard reference temperature of 530°R was used.

APPENDIX E

ASME TEST FORM FOR ABBREVIATED EFFICIENCY TEST

SUMMARY SHEET — PTC 4.1-a (1964)

					TEST NO		BOILER NO.		DATE	
OWNER OF PLANT					LOCATION					
TEST CONDUCTED BY					OBJECTIVE OF TEST				DURATION	
BOILER MAKE & TYPE								RATED CAPACITY		
STOKER TYPE & SIZE										
PULVERIZER, TYPE & SIZE								BURNER, TYPE & SIZE		
FUEL USED	MINE			COUNTY		STATE			SIZE AS FIRED	
PRESSURES & TEMPERATURES				**FUEL DATA**						
1	STEAM PRESSURE IN BOILER DRUM	psia			COAL AS FIRED PROX. ANALYSIS	% wt			OIL	
2	STEAM PRESSURE AT S. H. OUTLET	psia		37	MOISTURE		51	FLASH POINT F°		
3	STEAM PRESSURE AT R. H. INLET	psia		38	VOL MATTER		52	Sp. Gravity Deg. API*		
4	STEAM PRESSURE AT R. H. OUTLET	psia		39	FIXED CARBON		53	VISCOSITY AT SSU* BURNER SSF		
5	STEAM TEMPERATURE AT S. H. OUTLET	F		40	ASH		44	TOTAL HYDROGEN % wt		
6	STEAM TEMPERATURE AT R H INLET	F			TOTAL		41	Btu per lb		
7	STEAM TEMPERATURE AT R. H. OUTLET	F		41	Btu per lb AS FIRED					
8	WATER TEMP. ENTERING (ECON.) (BOILER)	F		42	ASH SOFT TEMP.* ASTM METHOD				GAS	% VOL
9	STEAM QUALITY % MOISTURE OR P. P. M.				COAL OR OIL AS FIRED ULTIMATE ANALYSIS		54	CO		
10	AIR TEMP. AROUND BOILER (AMBIENT)	F		43	CARBON		55	CH_4 METHANE		
11	TEMP. AIR FOR COMBUSTION (This is Reference Temperature) †	F		44	HYDROGEN		56	C_2H_2 ACETYLENE		
12	TEMPERATURE OF FUEL	F		45	OXYGEN		57	C_2H_4 ETHYLENE		
13	GAS TEMP. LEAVING (Boiler) (Econ.) (Air Htr.)	F		46	NITROGEN		58	C_2H_6 ETHANE		
14	GAS TEMP. ENTERING AH (If conditions to be corrected to guarantee)	F		47	SULPHUR		59	H_2S		
	UNIT QUANTITIES			40	ASH		60	CO_2		
15	ENTHALPY OF SAT. LIQUID (TOTAL HEAT)	Btu/lb		37	MOISTURE		61	H_2 HYDROGEN		
16	ENTHALPY OF (SATURATED) (SUPERHEATED) STM.	Btu/lb			TOTAL			TOTAL		
17	ENTHALPY OF SAT. FEED TO (BOILER) (ECON.)	Btu/lb			COAL PULVERIZATION			TOTAL HYDROGEN % wt		
18	ENTHALPY OF REHEATED STEAM R. H. INLET	Btu/lb		48	GRINDABILITY INDEX*		62	DENSITY 68 F ATM. PRESS.		
19	ENTHALPY OF REHEATED STEAM R. H. OUTLET	Btu/lb		49	FINENESS % THRU 50 M*		63	Btu PER CU FT		
20	HEAT ABS/LB OF STEAM (ITEM 16 – ITEM 17)	Btu/lb		50	FINENESS % THRU 200 M*		41	Btu PER LB		
21	HEAT ABS./LB R.H. STEAM (ITEM 19 – ITEM 18)	Btu/lb		64	INPUT-OUTPUT EFFICIENCY OF UNIT %		ITEM 31 × 100 / ITEM 29			
22	DRY REFUSE (ASH PIT + FLY ASH) PER LB AS FIRED FUEL	lb/lb			HEAT LOSS EFFICIENCY				Btu/lb A. F. FUEL	% of A. F. FUEL
23	Btu PER LB IN REFUSE (WEIGHTED AVERAGE)	Btu/lb		65	HEAT LOSS DUE TO DRY GAS					
24	CARBON BURNED PER LB AS FIRED FUEL	lb/lb		66	HEAT LOSS DUE TO MOISTURE IN FUEL					
25	DRY GAS PER LB AS FIRED FUEL BURNED	lb/lb		67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2					
	HOURLY QUANTITIES			68	HEAT LOSS DUE TO COMBUST. IN REFUSE					
26	ACTUAL WATER EVAPORATED	lb/hr		69	HEAT LOSS DUE TO RADIATION					
27	REHEAT STEAM FLOW	lb/hr		70	UNMEASURED LOSSES					
28	RATE OF FUEL FIRING (AS FIRED wt)	lb/hr		71	TOTAL					
29	TOTAL HEAT INPUT (Item 28 × Item 41) / 1000	kB/hr		72	EFFICIENCY = (100 – Item 71)					
30	HEAT OUTPUT IN BLOW-DOWN WATER	kB/hr								
31	TOTAL HEAT OUTPUT (Item 26 × Item 20) + (Item 27 × Item 21) + Item 30 / 1000	kB/hr								
	FLUE GAS ANAL. (BOILER) (ECON) (AIR HTR) OUTLET									
32	CO_2	% VOL								
33	O_2	% VOL								
34	CO	% VOL								
35	N_2 (BY DIFFERENCE)	% VOL								
36	EXCESS AIR	%								

* Not Required for Efficiency Testing

† For Point of Measurement See Par. 7.2.8.1-PTC 4.1-1964

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APPENDIX F

PTC 4.1-b (1964)

CALCULATION SHEET

ASME TEST FORM FOR ABBREVIATED EFFICIENCY TEST

Revised September, 1965

	OWNER OF PLANT	TEST NO.	BOILER NO.	DATE

30 HEAT OUTPUT IN BOILER BLOW-DOWN WATER = LB OF WATER BLOW-DOWN PER HR $\times \left[\frac{\text{ITEM 15} - \text{ITEM 17}}{1000}\right] =$ ..... kB/hr

24 *If impractical to weigh refuse, this item can be estimated as follows*

DRY REFUSE PER LB OF AS FIRED FUEL = $\frac{\text{\% ASH IN AS FIRED COAL}}{100 - \text{\% COMB. IN REFUSE SAMPLE}}$

CARBON BURNED PER LB AS FIRED FUEL = $\frac{\text{ITEM 43}}{100} - \left[\frac{\text{ITEM 22} \times \text{ITEM 23}}{14{,}500}\right] =$ .....

NOTE: IF FLUE DUST & ASH PIT REFUSE DIFFER MATERIALLY IN COMBUSTIBLE CONTENT, THEY SHOULD BE ESTIMATED SEPARATELY. SEE SECTION 7, COMPUTATIONS.

25 DRY GAS PER LB AS FIRED FUEL BURNED = $\frac{11CO_2 + 8O_2 + 7(N_2 + CO)}{3(CO_2 + CO)} \times$ (LB CARBON BURNED PER LB AS FIRED FUEL $+ \frac{3}{8}$ S)

$$= \frac{11 \times \frac{\text{ITEM 32}}{\text{.....}} + 8 \times \frac{\text{ITEM 33}}{\text{.....}} + 7\left(\frac{\text{ITEM 35}}{\text{.....}} - \frac{\text{ITEM 34}}{\text{.....}}\right)}{3 \times \left(\frac{\text{ITEM 32}}{\text{.....}} + \frac{\text{ITEM 34}}{\text{.....}}\right)} \times \left[\frac{\text{ITEM 24}}{\text{.....}} + \frac{\text{ITEM 47}}{267}\right] = \text{.....}$$

36 EXCESS AIR† $= 100 \times \frac{O_2 - \frac{CO}{2}}{.2682N_2 - (O_2 - \frac{CO}{2})} = 100 \times \frac{\text{ITEM 33} - \frac{\text{ITEM 34}}{2}}{.2682\,(\text{ITEM 35}) - (\text{ITEM 33} - \frac{\text{ITEM 34}}{2})} =$ .....

	HEAT LOSS EFFICIENCY	Btu/lb AS FIRED FUEL	$\frac{\text{LOSS}}{\text{HHV}} \times \frac{}{100} =$	LOSS %
65	HEAT LOSS DUE TO DRY GAS = LB DRY GAS PER LB AS FIRED FUEL $\times C_p \times (T_{\text{Lvg}} - T_{\text{air}}) = \frac{\text{ITEM 25}}{\text{Unit}} \times 0.24\,(\text{ITEM 13}) - (\text{ITEM 11}) =$	.....	$\frac{65}{41} \times 100 =$	.....
66	HEAT LOSS DUE TO MOISTURE IN FUEL = LB H_2O PER LB AS FIRED FUEL $\times$ [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = $\frac{\text{ITEM 37}}{100} \times$ [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) − (ENTHALPY OF LIQUID AT T ITEM 11)] = ...	.....	$\frac{66}{41} \times 100 =$	.....
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2 = $9H_2 \times$ [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] $= 9 \times \frac{\text{ITEM 44}}{100} \times$ [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) − (ENTHALPY OF LIQUID AT T ITEM 11)] = ...	.....	$\frac{67}{41} \times 100 =$	.....
68	HEAT LOSS DUE TO COMBUSTIBLE IN REFUSE = $\frac{\text{ITEM 22}}{\text{.....}} \times \frac{\text{ITEM 23}}{\text{.....}} =$	.....	$\frac{68}{41} \times 100 =$	.....
69	HEAT LOSS DUE TO RADIATION* = $\frac{\text{TOTAL BTU RADIATION LOSS PER HR}}{\text{LB AS FIRED FUEL} - \text{ITEM 28}}$	.....	$\frac{69}{41} \times 100 =$	.....
70	UNMEASURED LOSSES **	.....	$\frac{70}{41} \times 100 =$	.....
71	TOTAL	.....	.....	.....
72	EFFICIENCY = (100 − ITEM 71)	.....	.....	.....

† For rigorous determination of excess air see Appendix 9.2 – PTC 4.1-1964

* If losses are not measured, use ABMA Standard Radiation Loss Chart, Fig. 8, PTC 4.1-1964

** Unmeasured losses listed in PTC 4.1 but not tabulated above may be provided for by assigning a mutually agreed upon value for Item 70.

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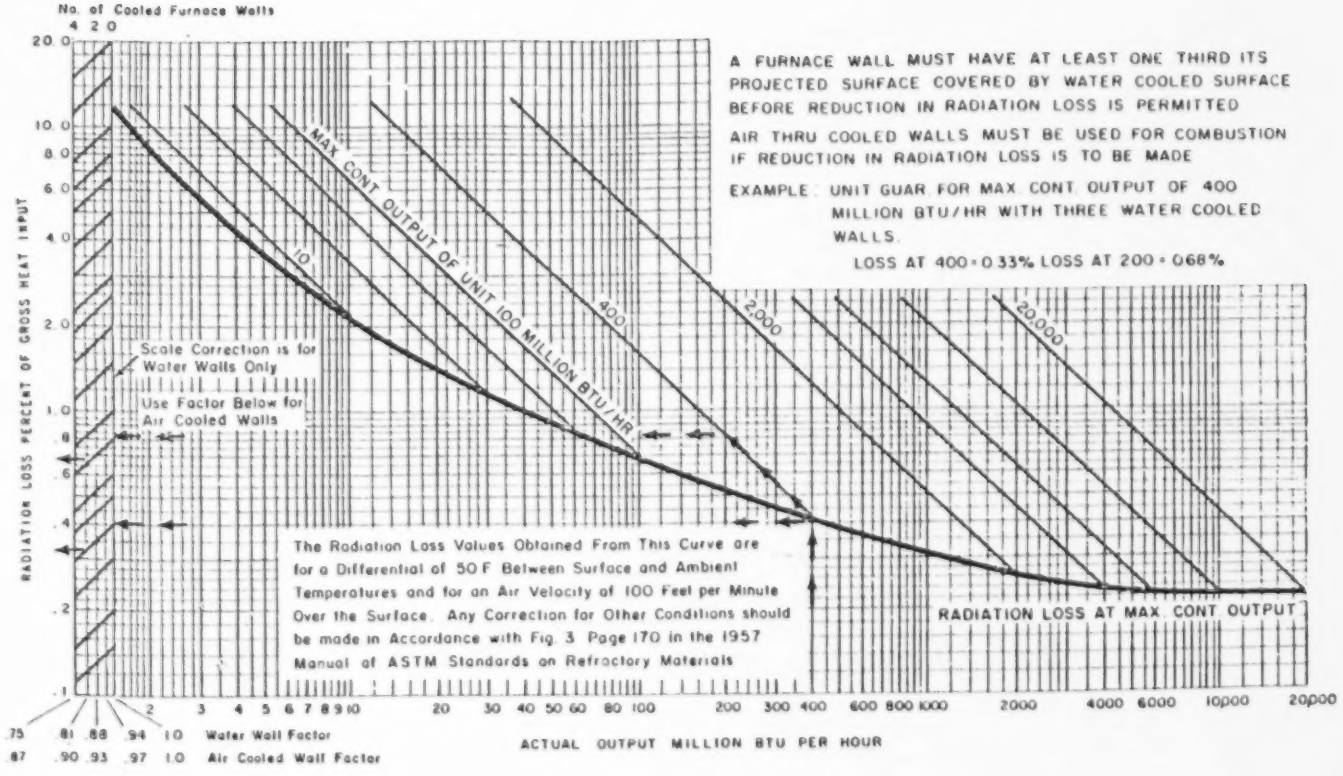
APPENDIX G

ABMA STANDARD RADIATION LOSS CHART


No. of Cooled Furnace Walls
4 2 0
RADIATION LOSS PERCENT OF GROSS HEAT INPUT
20.0
10.0
8.0
6.0
4.0
2.0
1.0
.8
.6
.4
.2
.1
MAX CONT OUTPUT OF UNIT 100 MILLION BTU/HR
10
400
2,000
20,000
Scale Correction is for Water Walls Only
Use Factor Below for Air Cooled Walls
A FURNACE WALL MUST HAVE AT LEAST ONE THIRD ITS PROJECTED SURFACE COVERED BY WATER COOLED SURFACE BEFORE REDUCTION IN RADIATION LOSS IS PERMITTED
AIR THRU COOLED WALLS MUST BE USED FOR COMBUSTION IF REDUCTION IN RADIATION LOSS IS TO BE MADE
EXAMPLE: UNIT GUAR FOR MAX. CONT. OUTPUT OF 400 MILLION BTU/HR WITH THREE WATER COOLED WALLS.
LOSS AT 400 = 0.33% LOSS AT 200 = 0.68%
The Radiation Loss Values Obtained From This Curve are for a Differential of 50 F Between Surface and Ambient Temperatures and for an Air Velocity of 100 Feet per Minute Over the Surface. Any Correction for Other Conditions should be made in Accordance with Fig. 3 Page 170 in the 1957 Manual of ASTM Standards on Refractory Materials
RADIATION LOSS AT MAX. CONT. OUTPUT
1 2 3 4 5 6 7 8 9 10 20 30 40 50 60 80 100 200 300 400 600 800 1000 2000 4000 6000 10000 20000
ACTUAL OUTPUT MILLION BTU PER HOUR
.75 .81 .88 .94 1.0 Water Wall Factor
.87 .90 .93 .97 1.0 Air Cooled Wall Factor